Numerical Weather Prediction

A Variational Rainfall Rate Analysis for Nimrod

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Abstract

The Nimrod Project is concerned with the generation of weather analyses and 0–6 hour forecast guidance for the UK and surrounding waters. As part of Nimrod, a Rainfall Rate Analysis (Activity 4.1) has been designed, coded, tuned and tested. The scheme uses a two-dimensional variational analysis to combine the various available data. This report describes the analysis scheme and presents the results from 10 case studies.

1 Rainfall Rate Analysis Scheme

1.1 Introduction

A rainfall rate analysis scheme has been developed for use within the Nimrod system.[1] The method and design of the analysis were laid out in a working paper [13], produced earlier in the year, although some necessary deviations from the planned approach have occurred. The scheme uses a two-dimensional variational (2DVAR) approach [7], applied to a transformed rainfall rate variable, $\mathbf{w}$, which is given by equation 1.

$$\begin{aligned} \mathbf{w} &= \ln\left(1 + \frac{\mathbf{x}}{a}\right) && \text{for } \mathbf{x} \geq 0.0 \\ \mathbf{w} &= \text{a measure of the "closeness to raining"} && \text{for } \mathbf{x} < 0.0 \end{aligned} \tag{1}$$

where $\mathbf{x}$ is the rainfall rate ($mm\,hr^{-1}$), and $a = 0.5333$ is a constant (calculated such that the differences between 0.0 $mm\,hr^{-1}$ and 0.5 $mm\,hr^{-1}$, and between 8.0 $mm\,hr^{-1}$ and 16.0 $mm\,hr^{-1}$ are equal in the transformed variable, $\mathbf{w}$).

The code structure splits into two main sections. The first, which could be termed 'data processing' reads in the rainfall rate data, converts it to $\mathbf{w}$ values, sets the error variances and generates a first-guess field. The second carries out the 'analysis'; calculating a quadratic penalty function (and its gradients), and applying a descent algorithm to minimise it. Additionally, two routines at the beginning of the program, set parameters for the rainfall rate analysis and set the date/time information respectively; and a routine at the end of the program writes out the final analysis. Table 1 summarises the analysis parameters, which are described in more detail in the following sections.

1.2 'Data Processing'

This section of the code reads in rainfall rate data derived from radar, satellite, forecast, Present Weather observations and sferics reports. These can be divided into two distinct classes, which are treated somewhat differently: the former three, which, henceforth, will be referred to as 'field data'; and the latter two, which will be referred to as 'weather reports'.

1.2.1 Field Data

The radar and forecast data are read in as fields of rainfall rate values.[2] The radar data will already have been processed to remove anaprop, and correct for 'bright-band', range and gauge measurements, as well as having the Area of Radar Cover (ARC) calculated [5].[3] The satellite data are read in as a series

[1] The Nimrod Project is concerned with the generation of weather analyses and 0–6 hour forecast guidance for the UK and surrounding waters [3]. The Nimrod system will be HP Workstation-based.

[2] In the operational Nimrod system, a 15 minute advection forecast from the previous analysis will be used. However, for testing purposes, a Mesoscale Model forecast is used.

[3] For testing purposes, the radar composite archived by the Nowcasting Development Group is used; this has a fixed Area of Radar Cover (ARC), which is larger than the Nimrod ARC, and does not have all the Nimrod corrections applied.

of classes (which have been derived from the infrared and visible Meteosat imagery [2]): 1, 2, 3 and 4, representing rainfall rates in excess of $\frac{1}{32}\ mm\,hr^{-1}$, $\frac{1}{8}\ mm\,hr^{-1}$, $\frac{1}{2}\ mm\,hr^{-1}$ and 2 $mm\,hr^{-1}$ respectively, and a cloud-mask field.

The field data are converted to **w** values using the equation 1. For radar and forecast data, dry areas have **w** set such that it decays exponentially with distance from rain, to a minimum value of $\mathbf{w}_{min}$ (-1.0). In this process, **w** is initally set equal to $\mathbf{w}_{min}$ for all dry pixels. Then, a number of scans in alternating directions reset these values using equation 2.

$$\mathbf{w}_{dry} = (\mathbf{w}_{max} - \mathbf{w}_{min}) \exp\left(-\frac{\Delta r}{s}\right) + \mathbf{w}_{min} \tag{2}$$

where $\mathbf{w}_{max}$ is the maximum value of **w** at an adjacent grid-square, $\mathbf{w}_{min}$ (-1.0) is the driest possible **w** value, s is the exponential fall-off scale and Δr (5 km) is the grid-spacing. For the satellite data, the **w** value set for each point is the mean of the upper and lower thresholds values; the cloud-mask is used (table 2).[4].

The radar data are assigned a fixed error variance of 0.2 (in terms of **w**). The satellite and forecast data are assigned an error variance by comparing the **w** values with the corresponding ones for the radar ('wet' radar pixels only), to calculate a 'correlation' variance', using equation 3

$$\begin{aligned} \mathbf{E}_{fd} &= \mathbf{E}_{corr} + \mathbf{E}_{rad} && \text{for } N_{wet} \geq N_{req} \\ \mathbf{E}_{fd} &= \tfrac{N_{wet}}{N_{req}}\mathbf{E}_{corr} + \left(1 - \tfrac{N_{wet}}{N_{req}}\right)\mathbf{E}_{def} + \mathbf{E}_{rad} && \text{for } N_{wet} < N_{req} \end{aligned} \tag{3}$$

where E is the error variance; and the subscripts *fd*, *rad*, *corr* and *def* denote field data (forecast or satellite), radar, correlation and default value for the field data. N_{wet} denotes the number of wet radar pixels and N_{req} the number of wet radar pixels required to use the correlation variance alone (4000 $\approx$ 20% of the radar domain).

1.2.2 'Weather Reports'

The Present Weather and cloud information contained in surface observations (SYNOP and SHIP reports) is used to define rainfall rate thresholds. The limits for the Present Weather code (and brief descriptions of the codes) are given in table 3; these are based on those used in the Moisture Observation Pre-processing System (MOPS) [12], with some revision made with reference to the Observer's Handbook [8]. The values are converted to **w** using equation 1. For the dry observations, the **w** values are assigned from the total cloud cover observation, as specified in table 4.

Sferics lightning location data [1] are treated in the same way as the Present Weather reports, but with a lower limit of 2 $mm\,hr^{-1}$ and an upper limit of 100 $mm\,hr^{-1}$.

All weather reports are assigned an error variance of 0.2 (in terms of **w**).

1.2.3 First-guess

The first-guess is set to an 'optimal' combination of the radar, satellite and forecast rainfall rates, ignoring the effect of correlated errors. This takes the form:

$$\mathbf{w}_{fg} = \frac{\sum\left(\frac{\mathbf{w}_{rad}}{E_{rad}}\right) + \sum\left(\frac{\mathbf{w}_{fc}}{E_{fc}}\right) + \sum\left(\frac{\mathbf{w}_{sat}}{E_{sat}}\right)}{\sum\left(\frac{1}{E_{rad}}\right) + \sum\left(\frac{1}{E_{fc}}\right) + \sum\left(\frac{1}{E_{sat}}\right)} \tag{4}$$

where **w** is the analysis variable; E is the error variance; and the subscripts *fg*, *rad*, *fc* and *sat* denote the first-guess, composite radar, forecast and satellite-derived values.

1.3 'Analysis'

This section of the scheme performs a variational analysis. All data are passed in as **w** values (or **w** limits in the case of the 'weather reports'). The solution is found by minimising a penalty function, using a descent algorithm (NAG routine E04DGF [9]), which uses a pre-conditioned, limited memory quasi-Newton conjugate gradient method).

[4] As no cloud mask was available for the test data, dry **w** values are set using equation 2

Parameter	Symbol	Value
ANALYSIS PARAMETERS		
First-guess Type		'Optimal' (1)
Satellite Error Type		Correlated Variance (1)
Forecast Error Type		Correlated Variance (1)
Radar Error Type		Fixed Variance (0)
Weather Report Error Type		Fixed Variance (0)
Radar Error Variance	$\mathbf{E}_{rad}$	0.20
Weather Report Error Variance	$\mathbf{E}_{wr}$	0.20
Default Satellite Correlation Variance	$\mathbf{E}_{def}$	1.00
Default Forecast Correlation Variance	$\mathbf{E}_{def}$	0.65
Required Number of Wet Radar Pixels	N_{req}	4000
Filter Type		Recursive Filter (1)
Number of Filter Passes		2
Analysis Filter Scale		1.0 grid-length (5 km)
Forecast Filter Scale		1.0 grid-length (5 km)
Radar Filter Scale		1.0 grid-length (5 km)
Satellite Filter Scale		1.0 grid-length (5 km)
InterpolationType		Bi-linear (1)
ANALYSIS VARIABLE ($\mathbf{w}$) PARAMETERS		
W_Constant	a	0.5333
W_Minimum	$\mathbf{w}_{min}$	-1.0
DryW_Scale	s	50.0 km
NumberOfDryW_Scans		10
DATA USAGE/TESTING PARAMETERS		
UseForecast		TRUE
UseRadar		TRUE
UseSatellite		TRUE
UseWeather		TRUE
TestAdjoint		FALSE
NAG DESCENT ALGORITHM PARAMETERS		
Verify_Level		-1
Print_Level		5
Iteration_Limit		500
Estimated_Optimal_Function_Value		Default
Function_Precision		1.0E-5
Optimality_Tolerance		0.5E-2
Linesearch_Tolerance		0.9

Table 1: The Analysis Parameters used to carry out the final testing of the rainfall rate analysis on the 10 case studies.

Class	threshold	w set	rainfall rate
-1	no cloud	$\mathbf{w}_{min}$ (-1.0)	0.0 $mm\,hr^{-1}$
0	cloud/no rain	0.0	0.0 $mm\,hr^{-1}$
1	> 0.03125 $mm\,hr^{-1}$	0.1338	0.07635 $mm\,hr^{-1}$
2	> 0.125 $mm\,hr^{-1}$	0.4360	0.2915 $mm\,hr^{-1}$
3	> 0.5 $mm\,hr^{-1}$	1.110	1.085 $mm\,hr^{-1}$
4	> 2.0 $mm\,hr^{-1}$	2.166	4.119 $mm\,hr^{-1}$

Table 2: The values of the transform variable, $\mathbf{w}$, and the corresponding rainfall rates, set for the satellite data.

Description	Code	Rain-rate thresholds	
		Lower	Upper
No precipitation at station	1—15	Use cloud observation	
Precipitation reaching the ground within 5km of the station	16	0.0	0.50
Thunder, but not precipitation at the station	17	0.0	2.00
No precipitation at station	18—49	Use cloud observation	
Intermittent slight drizzle	50	0.01	0.10
Continuous slight drizzle	51	0.02	0.10
Intermittent moderate drizzle	52	0.10	0.50
Continuous moderate drizzle	53	0.10	0.50
Intermittent heavy drizzle	54	0.50	1.00
Continuous heavy drizzle	55	0.50	1.00
Slight freezing drizzle	56	0.01	0.10
Moderate/heavy freezing drizzle	57	0.10	1.00
Slight drizzle and rain	58	0.02	0.50
Moderate/heavy drizzle and rain	59	0.50	4.00
Intermittent slight rain	60	0.02	0.50
Continuous slight rain	61	0.05	0.50
Intermittent moderate rain	62	0.50	4.00
Continuous moderate rain	63	0.50	4.00
Intermittent heavy rain	64	4.00	50.00
Continuous heavy rain	65	4.00	50.00
Slight freezing rain	66	0.02	0.50
Heavy freezing rain	67	0.50	4.00
Slight rain or drizzle and snow	68	0.01	0.50
Moderate/heavy rain and snow	69	0.50	50.00
Intermittent slight snow	70	0.01	0.50
Continuous slight snow	71	0.02	0.50
Intermittent moderate snow	72	0.50	4.00
Continuous moderate snow	73	0.50	4.00
Intermittent heavy snow	74	4.00	50.00
Continuous heavy snow	75	4.00	50.00
Diamond dust	76	Use cloud observation	
Snow grains	77	0.01	0.10
Isolated snow crystals	78	Use cloud observation	
Ice pellets	79	0.10	0.50
Slight rain showers	80	0.01	2.00
Moderate/heavy rain showers	81	2.00	50.00
Violent rain showers	82	50.00	100.00
Slight rain and snow showers	83	0.01	2.00
Moderate/heavy rain/snow showers	84	2.00	50.00
Slight snow showers	85	0.01	2.00
Moderate/heavy snow showers	86	2.00	50.00
Slight small hail showers	87	0.10	2.00
Moderate/heavy small hail showers	88	2.00	50.00
Slight hail showers	89	0.10	2.00
Moderate/heavy hail showers	90	2.00	50.00
Slight rain (Cb in previous hour)	91	0.10	0.50
Moderate/heavy rain (Cb previous hr)	92	0.50	50.00
Slight snow (Cb in previous hour)	93	0.10	0.50
Moderate/heavy snow (Cb previous hr)	94	0.50	50.00
Slight/moderate thunderstorm	95	0.10	10.00
Slight/moderate thunderstorm(hail)	96	0.10	10.00
Heavy thunderstorm	97	10.00	100.00
Heavy thunderstorm with dust storm	98	10.00	100.00
Heavy thunderstorm (hail)	99	10.00	100.00

Table 3: Precipitation rates thresholds ($mm\,hr^{-1}$) associated with Present Weather codes.

	Cloud classes		
Observed cloud cover	0—2	3—5	6—8
Lower w threshold	-1.00	-0.66	-0.33
Upper w threshold	-0.66	-0.33	0.00

Table 4: Ranges of **w** used for total cloud cover observation ranges.

The penalty function, **J**, consists of a number of quadratic terms (based on the assumption of a Gaussian error distribution) measuring the distance of the analysis from the data ($\mathbf{w}_{data}$- **w**), one for each data source. Each penalty function term, $\mathbf{J}_{data}$, involves the error covariance matrix, $\mathbf{O}_{data}$ and takes the form:

$$\mathbf{J}_{data} = \frac{1}{2} \left(\mathbf{w}_{data} - \mathbf{w}\right)^T \mathbf{O}_{data}^{-1} \left(\mathbf{w}_{data} - \mathbf{w}\right) \tag{5}$$

To make the problem soluble, the error covariance matrix is replaced by the error variance, $\mathbf{E}_{data}$, with the error correlations being approximated by the action of a filter, $\mathbf{U}_{data}$; the inverse of error correlation is represented by an inverse filter (or de-smoother), $\mathbf{T}_{data}$[6] The Penalty function, then, takes the form:

$$\mathbf{J}_{data} = \frac{1}{2} \left(\mathbf{T}_{data}(\mathbf{w}_{data} - \mathbf{w})\right)^T \mathbf{E}_{data}^{-1} \left(\mathbf{T}_{data}(\mathbf{w}_{data} - \mathbf{w})\right) \tag{6}$$

To improve the convergence of the solution, the NAG routine carries out the minimisation not in terms of **w**, but a conditioned increment variable, **v**, computed by applying the de-smoother to the difference between the analysis value, **w**, and the first-guess value, $\mathbf{w}_{fg}$ (equation 7).

$$\mathbf{v} = \mathbf{T}(\mathbf{w}_{fg} - \mathbf{w}) \tag{7}$$

In addition to the penalty function, **J**, the gradient of the penalty function, $\frac{\partial \mathbf{J}}{\partial \mathbf{v}}$ is also required; this involves adjoints of the filter and inverse filter. The form of the penalty function term and its gradient for field data are given in equation 8 (symbols have the meaning assigned above, with the subscripts *fd* and *fg* denoting field data and first-guess, respectively).

$$\begin{aligned} \mathbf{J}_{fd} &= \tfrac{1}{2} \left(\mathbf{T}_{fd}(\mathbf{w}_{fd} - (\mathbf{w}_{fg} + \mathbf{U}\mathbf{v}))\right)^T \mathbf{E}_{fd}^{-1} \left(\mathbf{T}_{fd}(\mathbf{w}_{fd} - (\mathbf{w}_{fg} + \mathbf{U}\mathbf{v}))\right) \\ \frac{\partial \mathbf{J}_{fd}}{\partial \mathbf{v}} &= \mathbf{U}^* \mathbf{T}_{fd}^* \mathbf{E}_{fd}^{-1} \left(\mathbf{T}_{fd}(\mathbf{w}_{fd} - (\mathbf{w}_{fg} + \mathbf{U}\mathbf{v}))\right) \end{aligned} \tag{8}$$

The weather reports are assumed to be uncorrelated, so the $(\mathbf{w}_{data} - \mathbf{w})$ values are unfiltered, but an interpolation operator, $\mathbf{K}_{wr}$ (and its adjoint, $\mathbf{K}_{wr}^*$) is required to map the analysis grid-point values on to the observation points. The form of the penalty function term and its gradient for weather reports are shown in equation 9 (symbols have the meaning assigned above, with the subscript *wr* denoting weather reports, and *upper* and *lower* referring to the upper and lower limit values for the weather reports).

For $\mathbf{K}_{wr}(\mathbf{w}_{fg} + \mathbf{U}\mathbf{v}) < \mathbf{w}_{wrlower}$:

$$\begin{aligned} \mathbf{J}_{wr} &= \tfrac{1}{2}\left(\mathbf{w}_{wrlower} - \mathbf{K}_{wr}(\mathbf{w}_{fg} + \mathbf{U}\mathbf{v})\right)^T \mathbf{E}_{wr}^{-1}\left(\mathbf{w}_{wrlower} - \mathbf{K}_{wr}(\mathbf{w}_{fg} + \mathbf{U}\mathbf{v})\right) \\ \frac{\partial \mathbf{J}_{wr}}{\partial \mathbf{v}} &= \mathbf{U}^*\mathbf{K}_{wr}^*\mathbf{E}_{wr}^{-1}\left(\mathbf{w}_{wrlower} - \mathbf{K}_{wr}(\mathbf{w}_{fg} + \mathbf{U}\mathbf{v})\right) \end{aligned}$$

For $\mathbf{w}_{wrlower} < \mathbf{K}_{wr}(\mathbf{w}_{fg} + \mathbf{U}\mathbf{v}) < \mathbf{w}_{wrupper}$:

$$\begin{aligned} \mathbf{J}_{wr} &= 0 \\ \frac{\partial \mathbf{J}_{wr}}{\partial \mathbf{v}} &= 0 \end{aligned} \tag{9}$$

For $\mathbf{K}_{wr}(\mathbf{w}_{fg} + \mathbf{U}\mathbf{v}) > \mathbf{w}_{wrupper}$:

$$\begin{aligned} \mathbf{J}_{wr} &= \tfrac{1}{2}\left(\mathbf{K}_{wr}(\mathbf{w}_{fg} + \mathbf{U}\mathbf{v}) - \mathbf{w}_{wrupper}\right)^T \mathbf{E}_{wr}^{-1}\left(\mathbf{K}_{wr}(\mathbf{w}_{fg} + \mathbf{U}\mathbf{v}) - \mathbf{w}_{wrupper}\right) \\ \frac{\partial \mathbf{J}_{wr}}{\partial \mathbf{v}} &= \mathbf{U}^*\mathbf{K}_{wr}^*\mathbf{E}_{wr}^{-1}\left(\mathbf{K}_{wr}(\mathbf{w}_{fg} + \mathbf{U}\mathbf{v}) - \mathbf{w}_{wrupper}\right) \end{aligned}$$

As explained earlier, the representation of correlated errors and the conditioning of the analysis variable are carried out using a filters. For this purpose, it was decided to adopt a recursive filter [10], as routines to apply the filter (and its inverse, adjoint and inverse adjoint) were already written as part of the 2DVAR test system [11].

Some time was spent investigating the effect of varying the filter scales for the different data types. The filter scale for a particular data type, affects how the $(\mathbf{w}_{data} - \mathbf{w})$ increments from other data sources are smoothed with respect to it; this is particularly relevant for the spreading of the weather report increments. The Analysis filter scale, is used in the transformation to the conditioned increment variable $\mathbf{v}$, but does, in some sense, reflect the scale of the final analysis, and should be set equal to the largest of the data filter scales.

Neither the radar data nor the satellite data appear spatially correlated (although this is not strictly true for their errors). The model forecast data are correlated on a scale of at least 17 km, simply because of the model grid-spacing. However, running with a filtering scale of 20 km (4 grid-lengths) for the forecast and analysis produces a rather smooth analysis, removing desirable detail from within the radar domain, so all the filter scales have been set to 5 km (1 grid-length). This does mean the error correlations in the model forecast are not treated correctly, but in the operational scheme, this will be replaced by the 5 km advection forecast. The weather reports have quite a limited area of influence, but this is probably appropriate in view of the resolution of the other data sources.

1.4 Timings

Of interest to the operational implementation is the time taken for the rainfall rate analysis to run. The average elapse time for the 10 cases was 152 seconds. This was running with optimised code, a larger set of diagnostics than would be used operationally (including the writing out of fields of data), not stand alone and on equipment less powerful than the Nimrod hardware.

2 Case Study Results

To test the rainfall rate analysis scheme, 10 cases, covering a range of synoptic types, were selected. The cases were also chosen to be the same as those used in the testing of either the rain advection forecast scheme or the cloud advection forecast scheme of the Nimrod system. For each case, two figures are included: the first shows the rainfall rates from the satellite, radar, forecast and analysis; the second shows the Meteosat infrared image and the Present Weather codes from the surface reports (table 3 can be referenced for the definitions). The absence of the satellite rainfall rates in two of the figures,

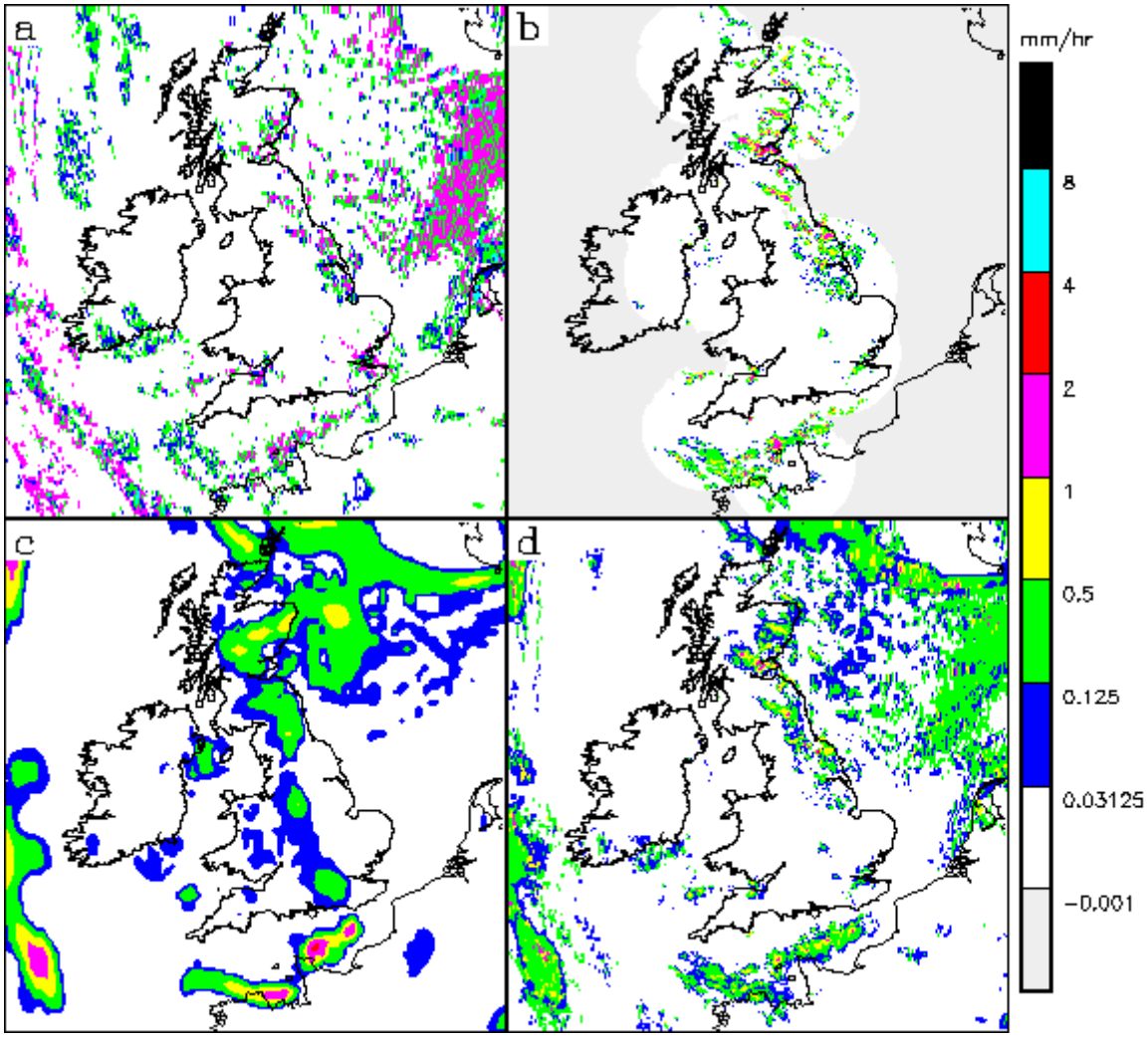

Figure 1: Rainfall Rate ($mm\,hr^{-1}$) for 1000 UTC 21st November 1993: a) Satellite-derived rate, b) Composite Radar image, c) Mesoscale Model forecast, d) Analysis.

reflects the unavailability of the data. A brief description of the synoptic situation and a discussion of the pertinent details of the analysis are given for each case. The main points are summarised and discussed in section 2.11.

2.1 1000 UTC 21st November 1993

A cold, easterly airsteam covered the UK, with temperatures remaining close to freezing. Snow showers were running into the east coast, and a marked land breeze convergence was producing precipitation over the English Channel.

The lines of precipitation streaming onto the east coast, are slightly reduced in intensity in the analysis, as compared with the radar. The showers over the North Sea are fairly well represented. It is not clear, whether the bands of rain to the west of Scotland, which are present in the satellite rain field, but not in the analysis, are correct or not; although the radar shows precipitation further south, it does not have any to the west of Scotland. The forecast (T+10 from 0000 UTC), has an erroneous band of snow lying down the middle of the country, which is successfully removed from the final analysis. An observation of a moderate shower over Grampian successfully introduces precipitation despite little support from other data sources. There is also an increase (correctly so) in the snow over southern England, as a result of the use of the Present Weather observations, although with reports of only light precipitation, the increase is small.

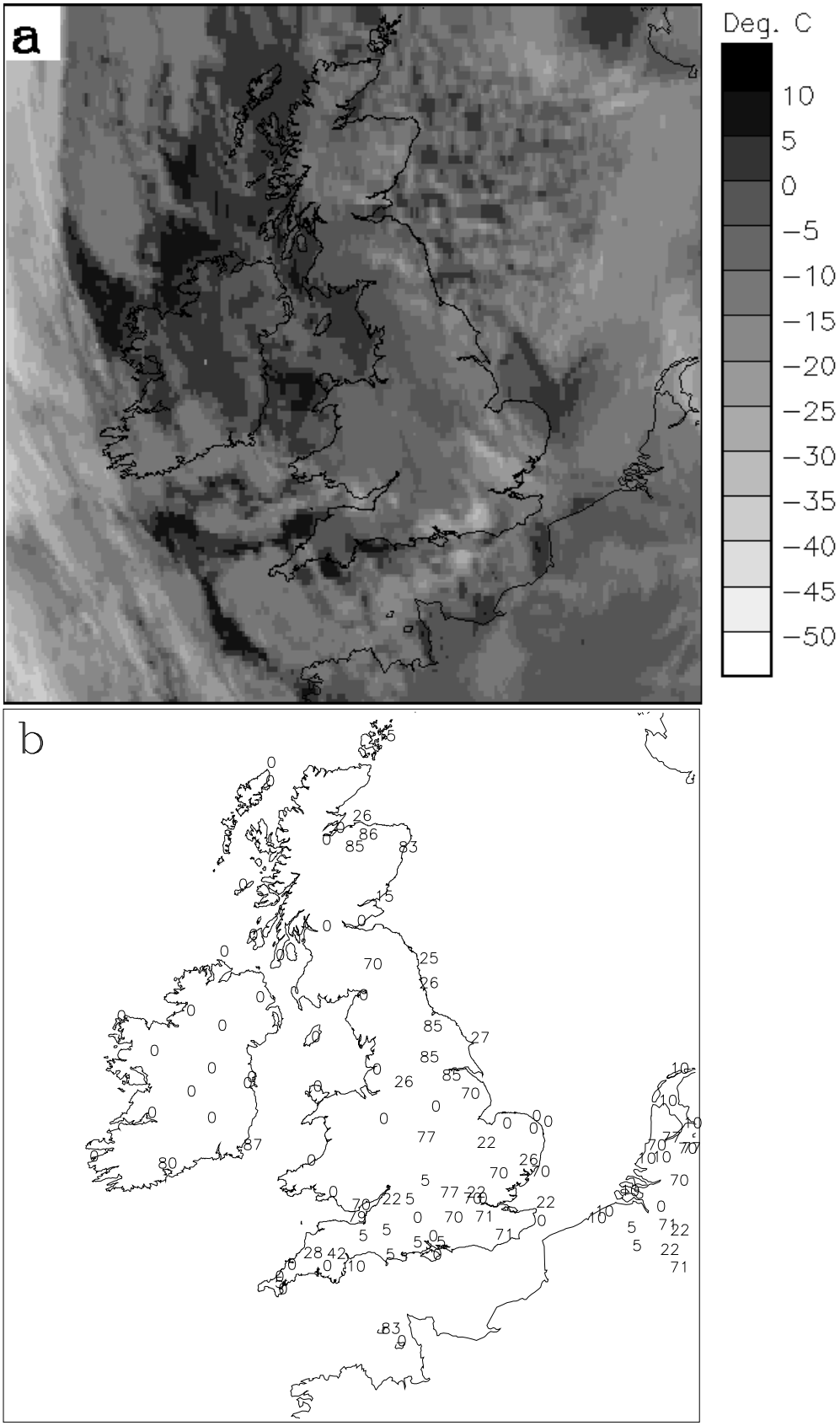

Figure 2: Observations for 1000 UTC 21st November 1993: a) Infrared Meteosat image, b) Present Weather Code Observations.

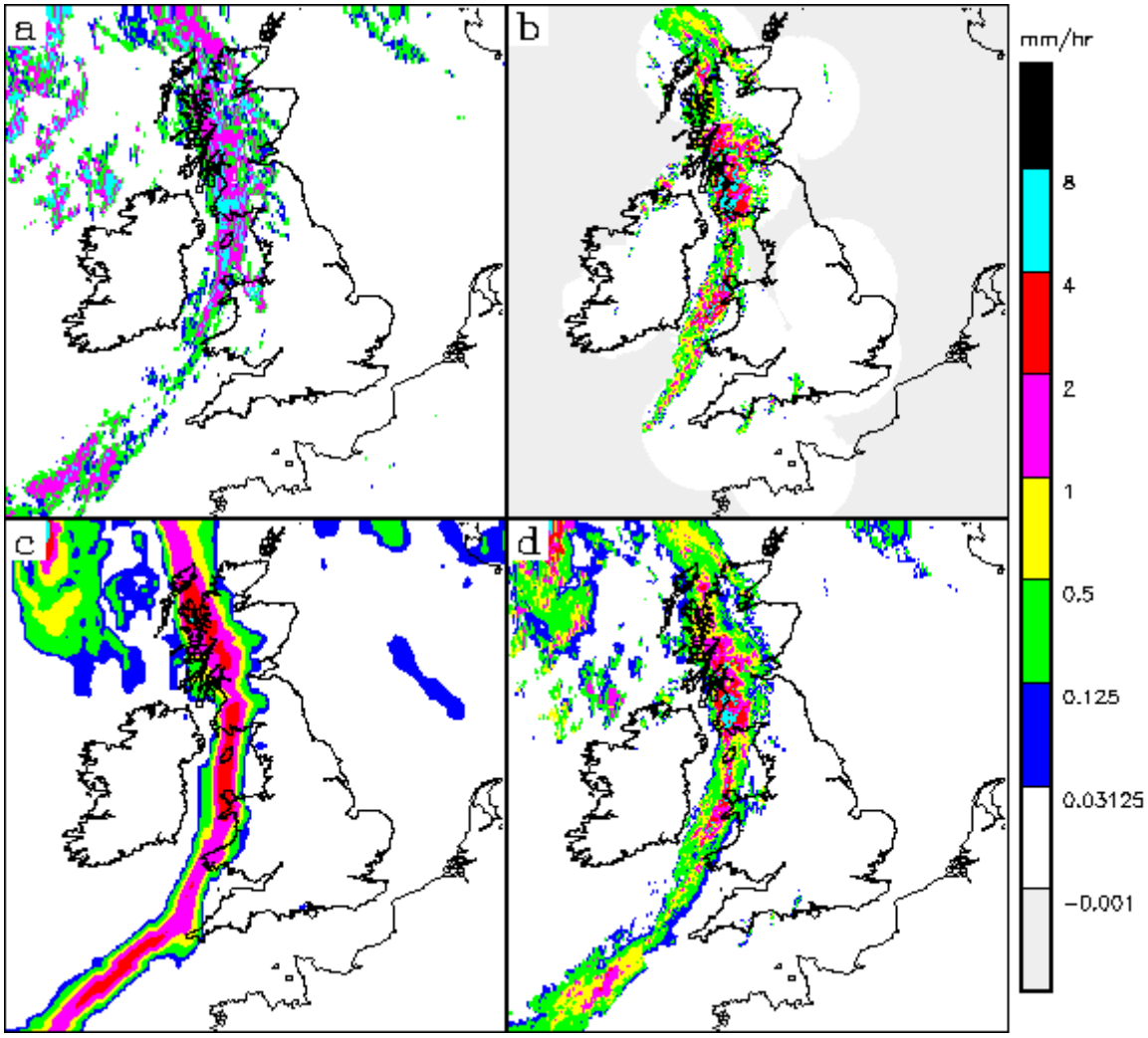

Figure 3: Rainfall Rate ($mm\,hr^{-1}$) for 1200 UTC 25th November 1993: a) Satellite-derived rate, b) Composite Radar image, c) Mesoscale Model forecast, d) Analysis.

2.2 1200 UTC 25th November 1993

A thin, but very marked, cold front moved across the UK from the west.

The radar, forecast and satellite precipitation fields agree fairly well, resulting in a realistic representation of the front, and the maintenance of the radar intensities. The model provides a rather smooth representation of the showers in the north-west, whereas the satellite picks out the individual showers; the analysis, a combination of the two, is probably too solid. The erroneous-looking light rain over the North Sea in the model forecast is removed from the analysis.

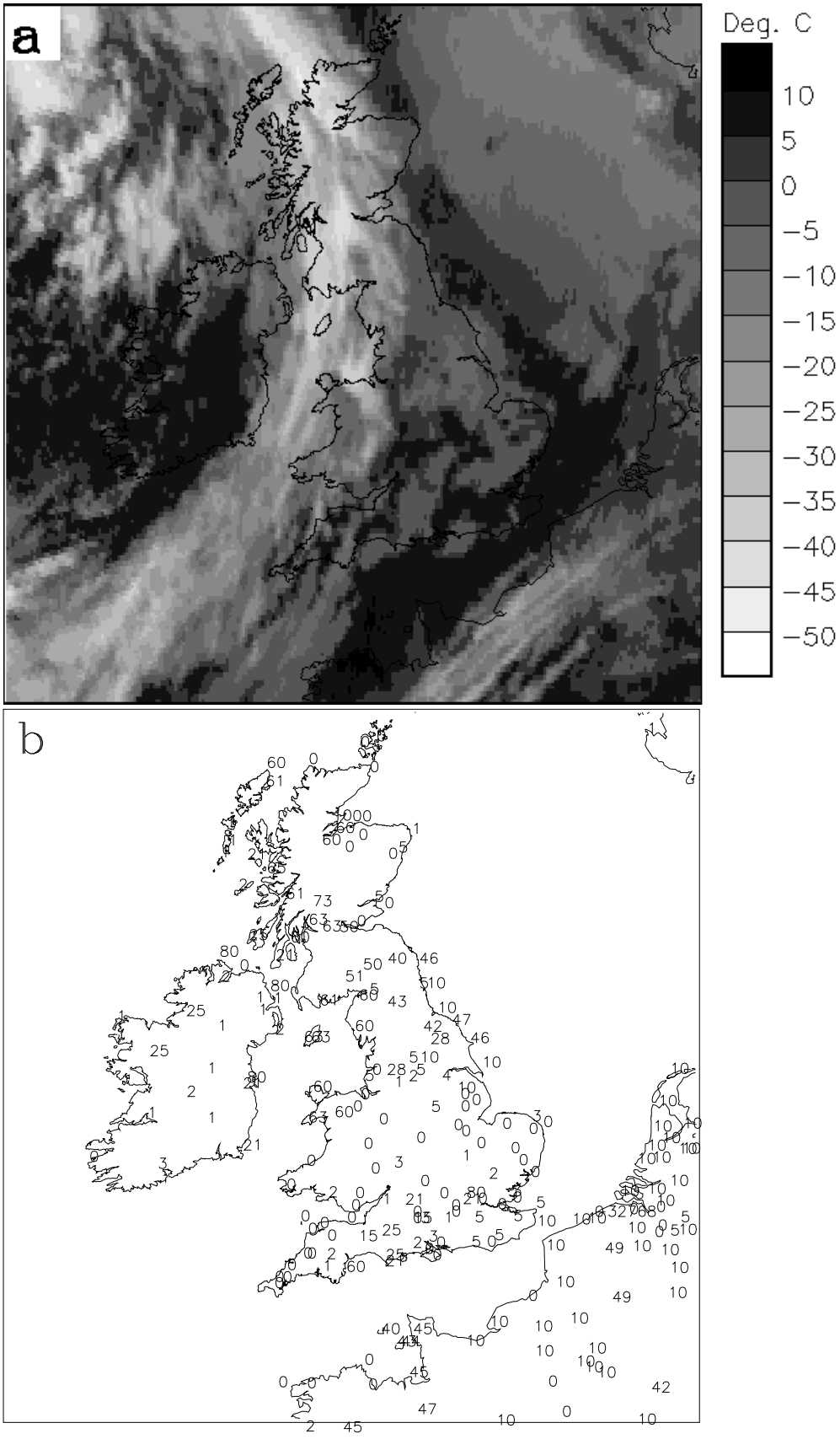

Figure 4: Observations for 1200 UTC 25th November 1993: a) Infrared Meteosat image, b) Present Weather Code Observations.

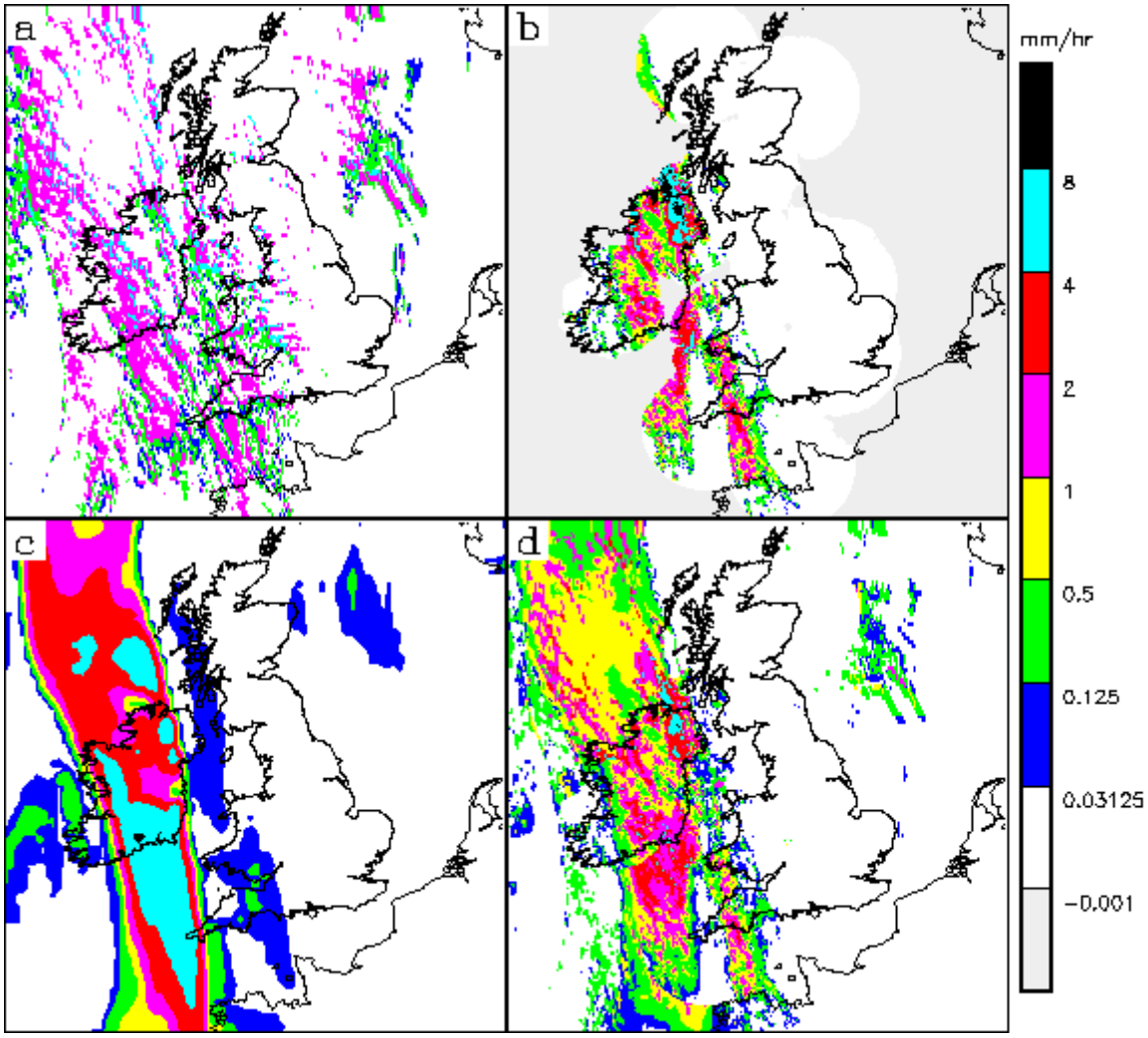

Figure 5: Rainfall Rate ($mm\,hr^{-1}$) for 1300 UTC 29th November 1993: a) Satellite-derived rate, b) Composite Radar image, c) Mesoscale Model forecast, d) Analysis.

2.3 1300 UTC 29th November 1993

A very active cold front moved in from the west, with southerly winds ahead of it.

The satellite provides a very poor representation of the rainfall, which is correlated with the medium cloud, but the forecast fills in the frontal rain outside the radar domain. It is not clear whether the area of rain over the North Sea is spurious or not; there is an observation just to the north of the domain showing continuous heavy drizzle.

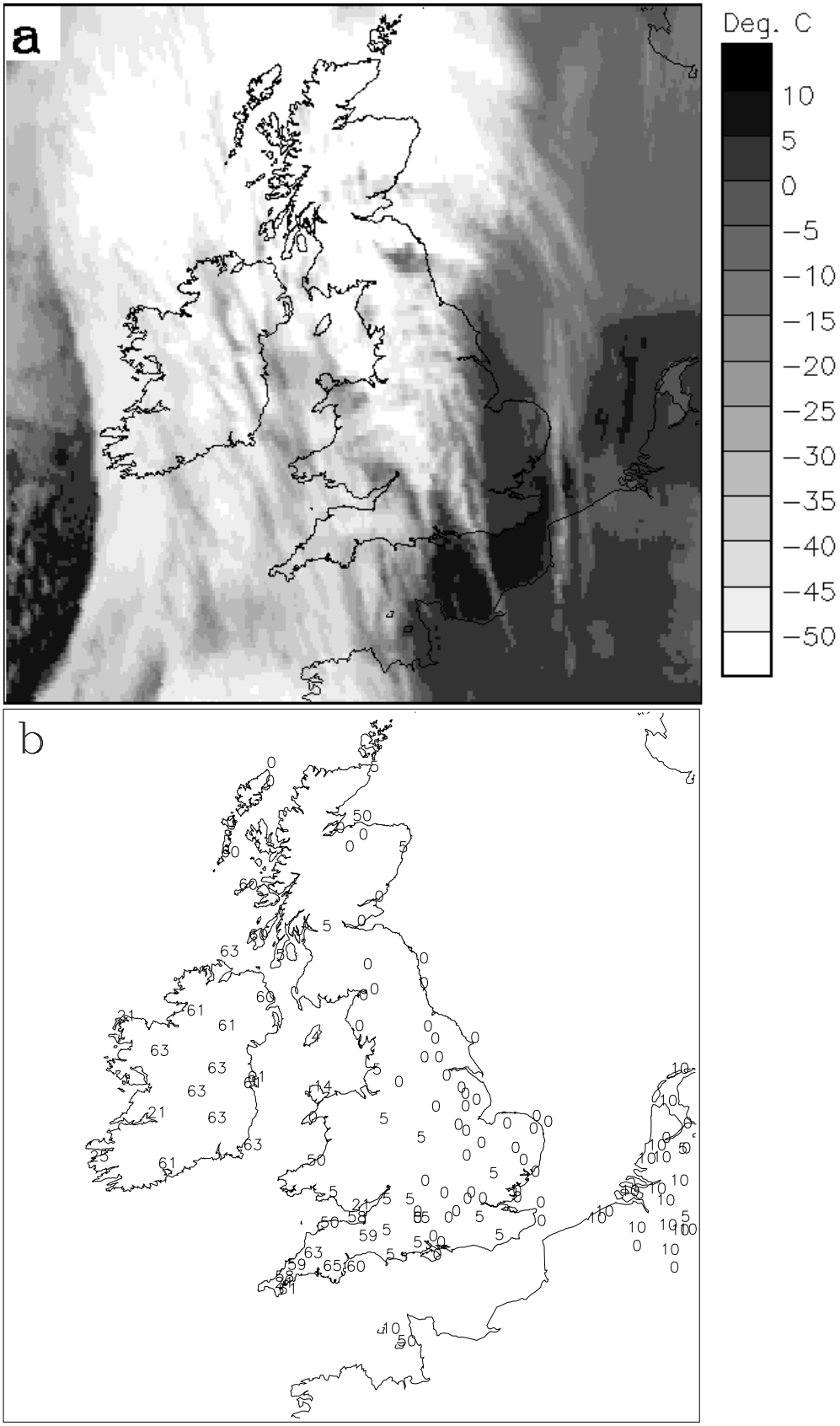

Figure 6: Observations for 1300 UTC 29th November 1993: a) Infrared Meteosat image, b) Present Weather Code Observations.

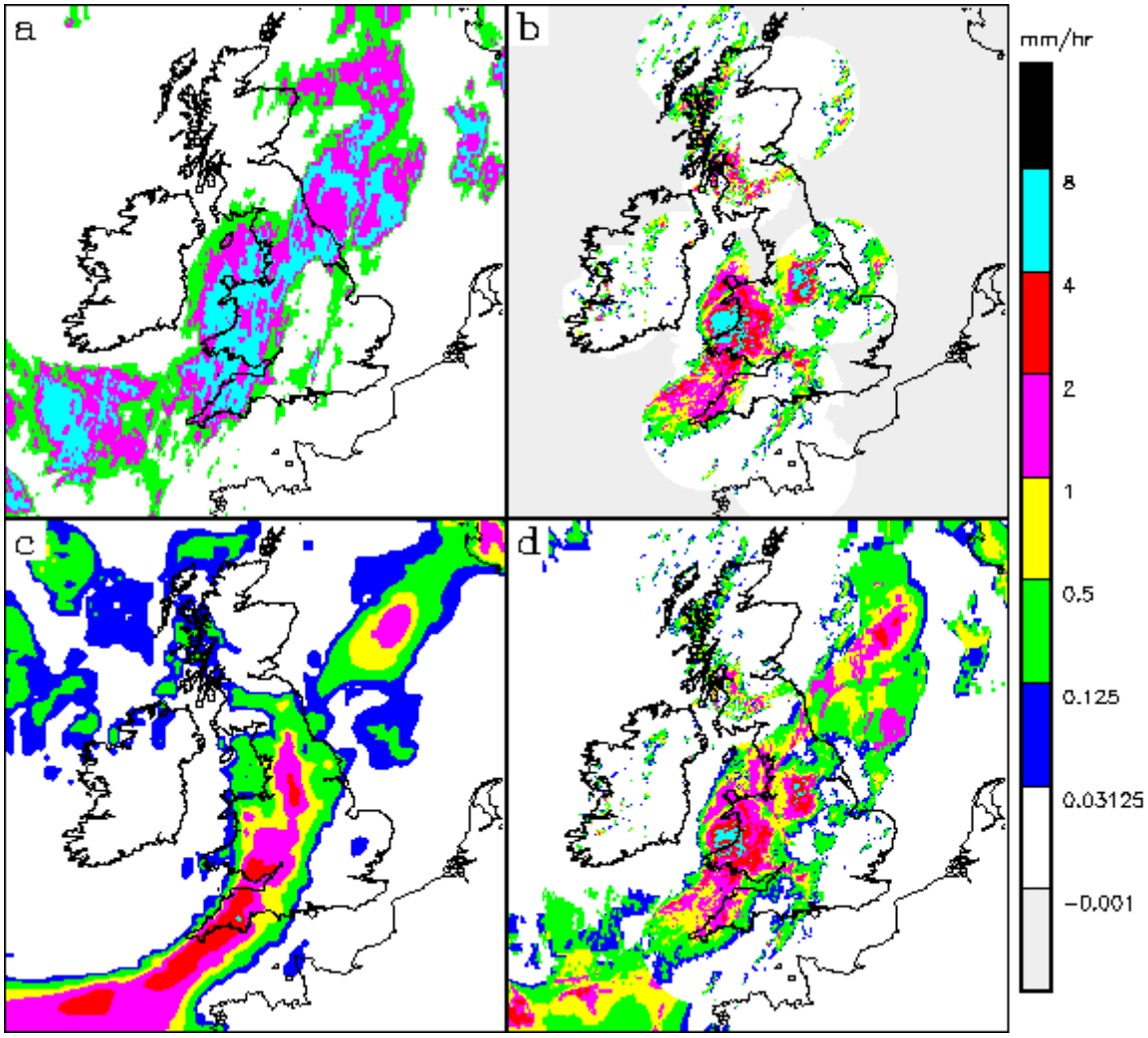

Figure 7: Rainfall Rate ($mm\,hr^{-1}$) for 0000 UTC 7th December 1993: a) Satellite-derived rate, b) Composite Radar image, c) Mesoscale Model forecast, d) Analysis.

2.4 0000 UTC 7th December 1993

A waving cold front crossed the UK from the west.

The model rain dominates in the south-west corner of the domain, because of its high intensities. Conversely in the north-west some of the lighter model rain is removed. The showers, which are shown in the forecast and are probably real, are removed from the analysis, by the satellite data, which, perhaps surprisingly, does not pick up them up; the MOPS analysis would have maintained an area of precipitation here.

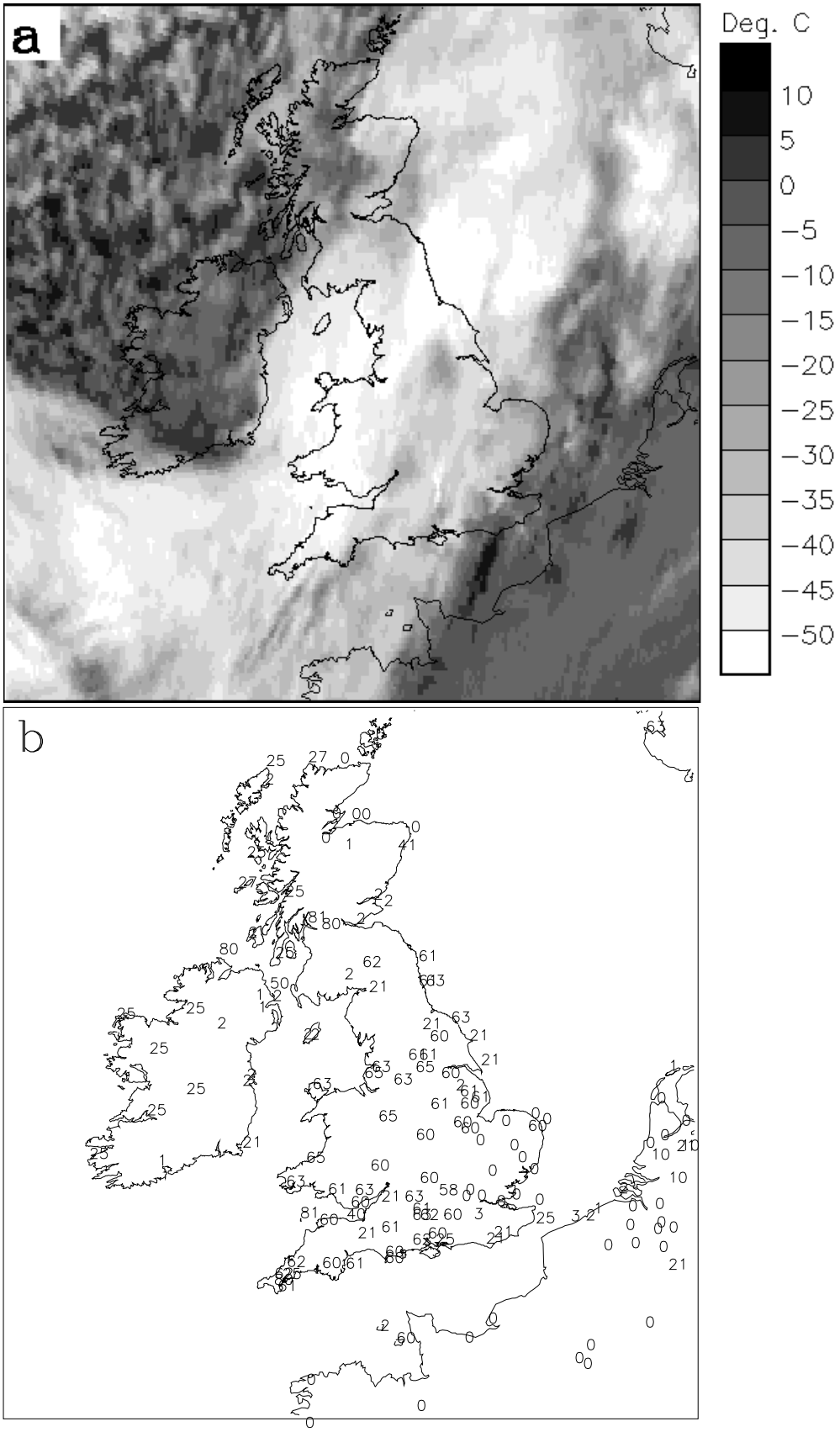

Figure 8: Observations for 0000 UTC 7th December 1993: a) Infrared Meteosat image, b) Present Weather Code Observations.

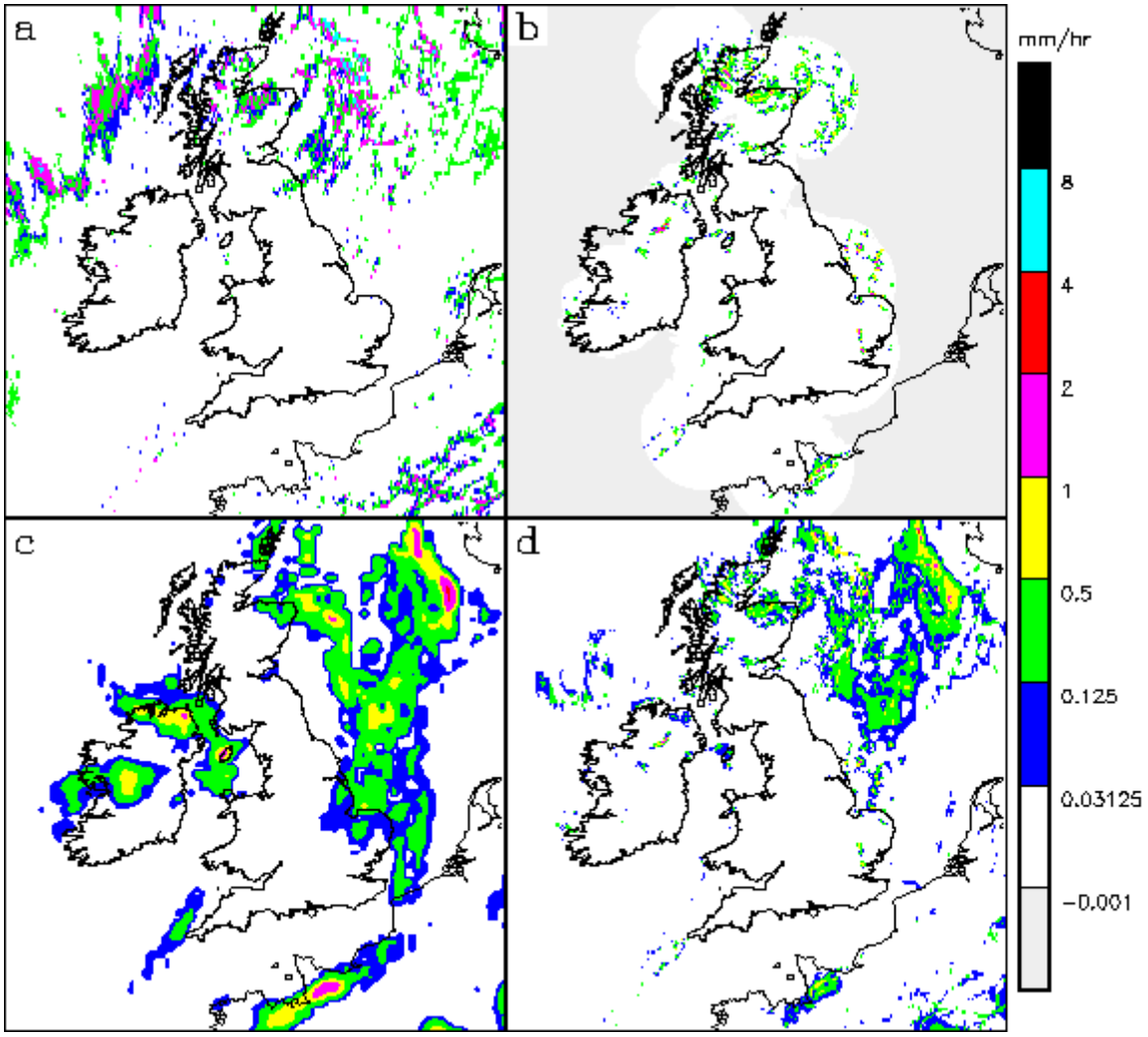

Figure 9: Rainfall Rate ($mm\,hr^{-1}$) for 1400 UTC 16th January 1994: a) Satellite-derived rate, b) Composite Radar image, c) Mesoscale Model forecast, d) Analysis.

2.5 1400 UTC 16th January 1994

A northerly flow was bringing wintry showers to north and east coasts. A depression was just beginning to edge into the domain from the west.

The satellite classification scheme has associated rain with the medium-level cloud of the incoming depression, which is almost certainly erroneous, and is not present in the analysis due to the influence of the forecast. The showery precipitation over the North Sea appears too widespread as a result of the smoother model forecast field.

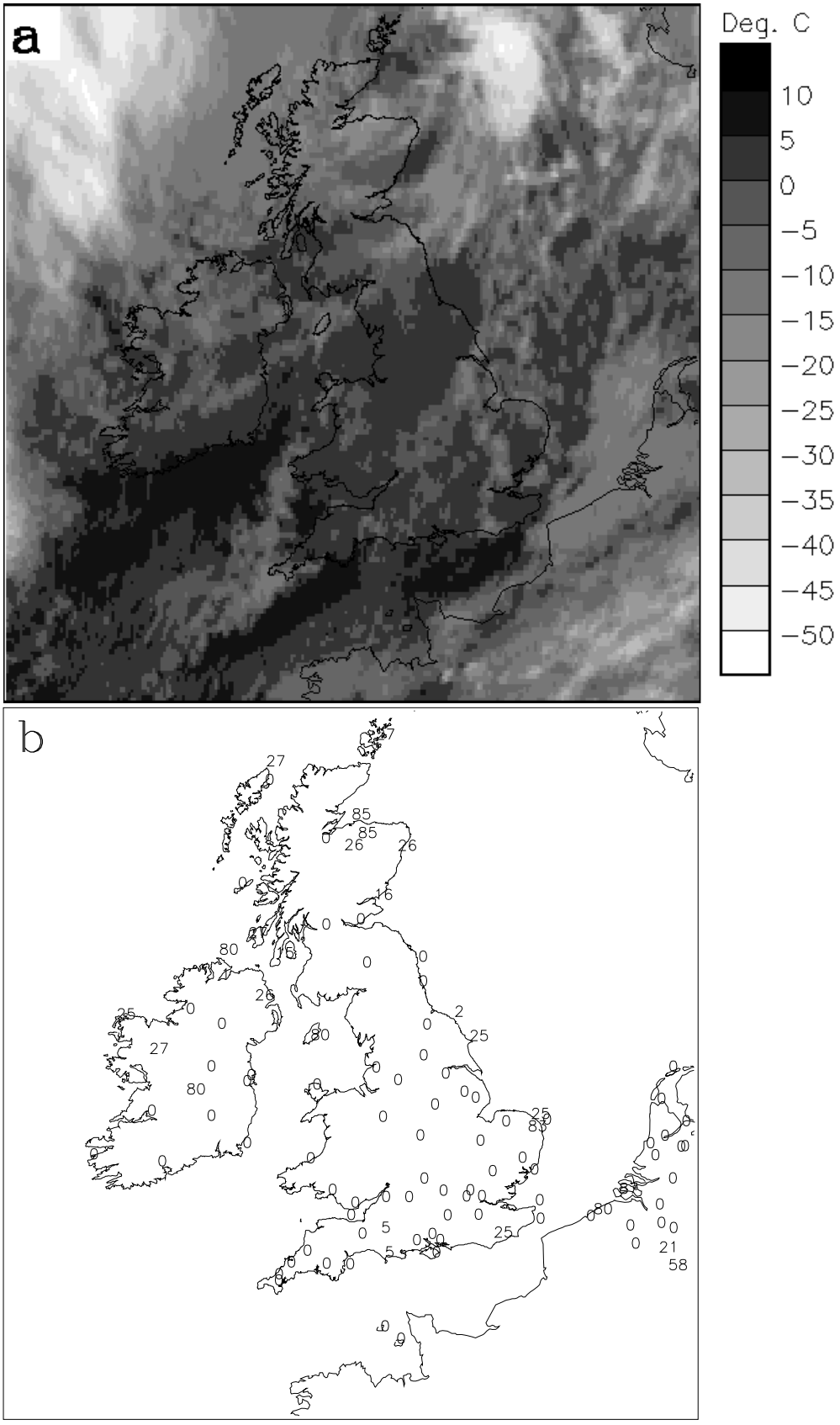

Figure 10: Observations for 1400 UTC 16th January 1994: a) Infrared Meteosat image, b) Present Weather Code Observations.

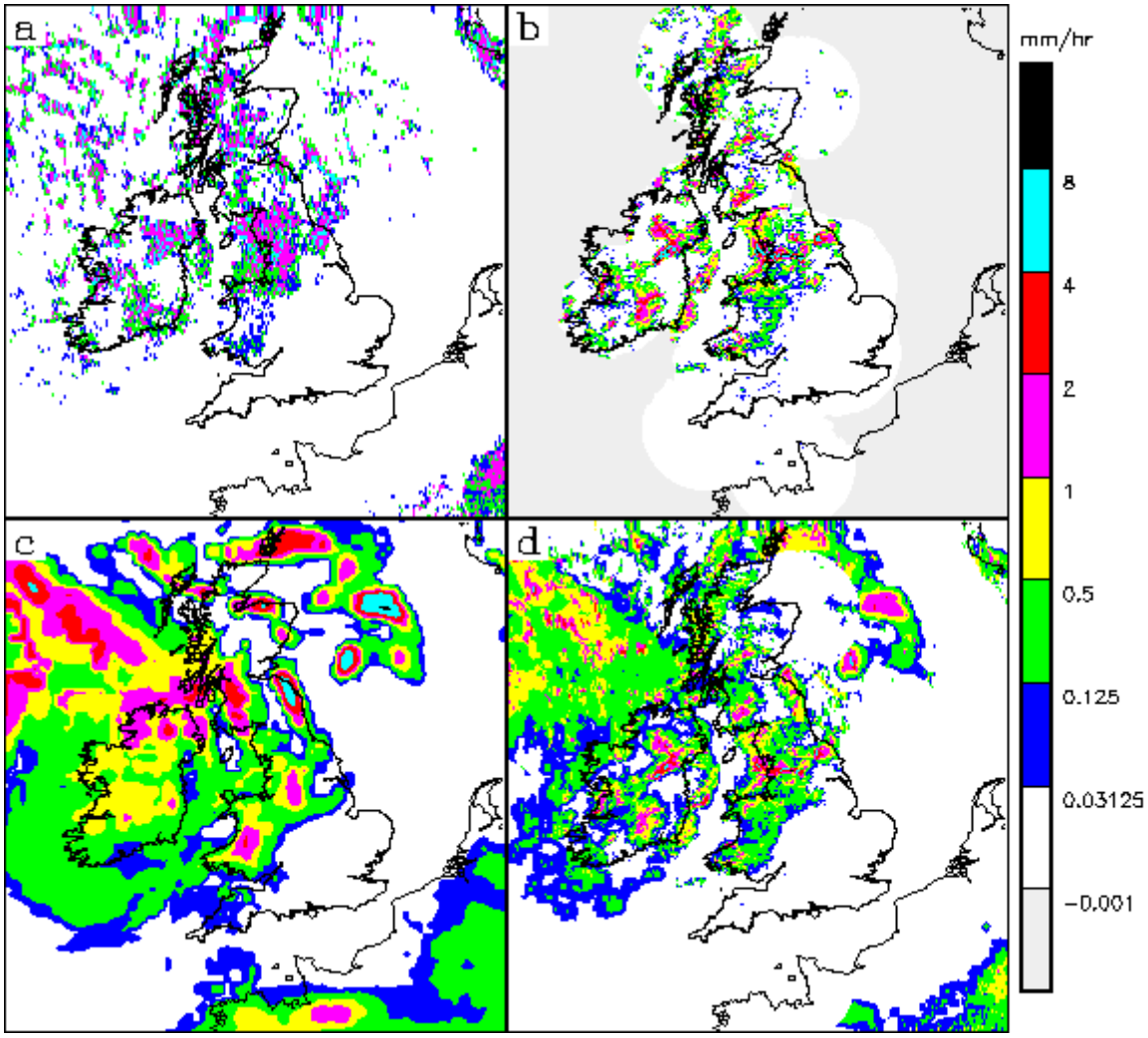

Figure 11: Rainfall Rate ($mm\,hr^{-1}$) for 1500 UTC 25th January 1994: a) Satellite-derived rate, b) Composite Radar image, c) Mesoscale Model forecast, d) Analysis.

2.6 1500 UTC 25th January 1994

Following a cold front, which was leaving the domain to the southeast, an area of organised, heavy showers was moving into the UK in a strong westerly flow.

The use of the model forecast has resulted in a solid area of precipitation in the analysis to the northwest of the UK, rather than showers with gaps in between. It has also tended to 'fill in' the gaps within the radar domain, which looks over-done, although virtually all the surface observations do indicate rain; the radar intensities, however, have been maintained in the analysis. The drizzle over France is not picked up very well in the analysis, but this is primarily because it is not picked up by the radar.

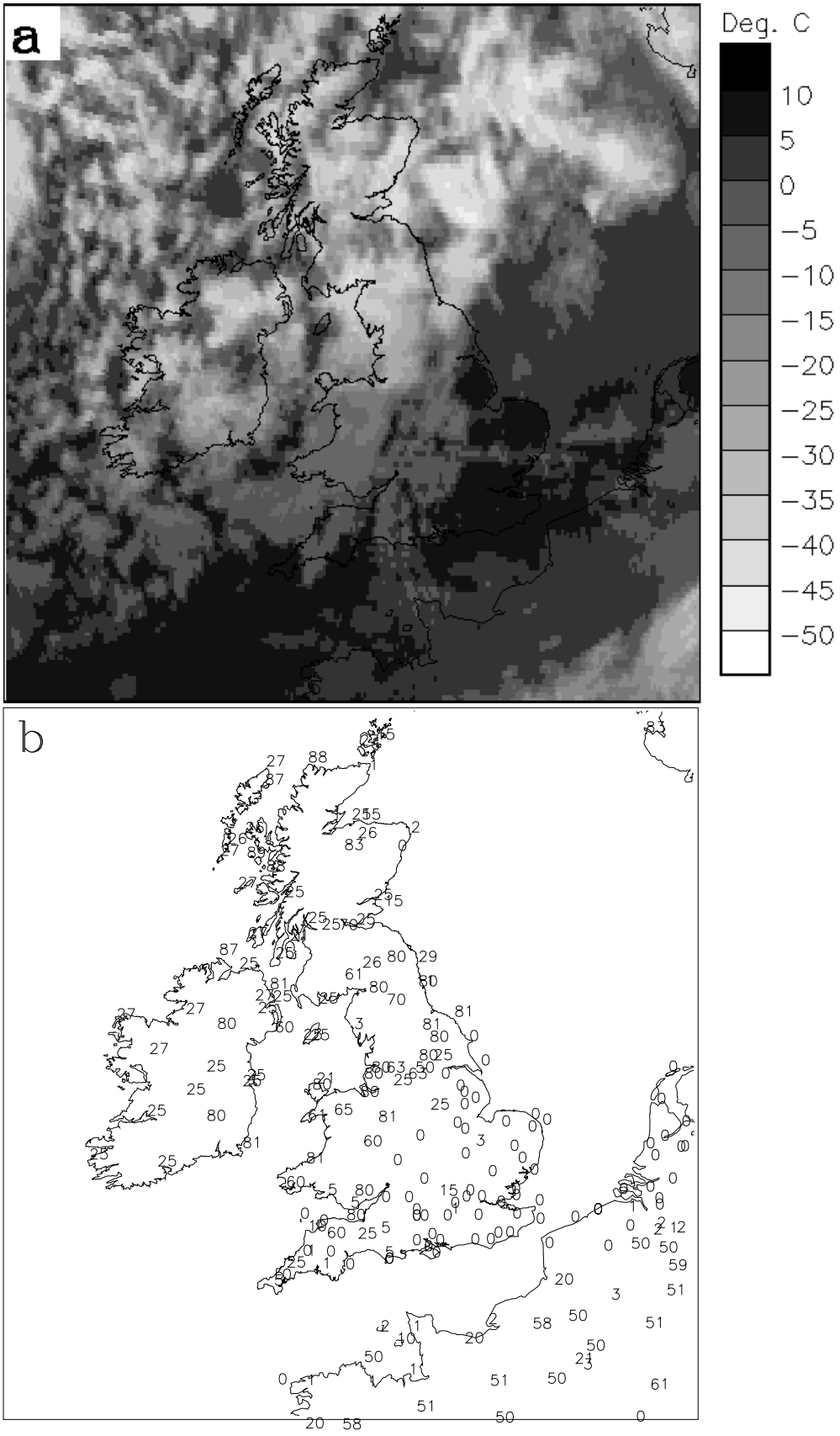

Figure 12: Observations for 1500 UTC 25th January 1994: a) Infrared Meteosat image, b) Present Weather Code Observations.

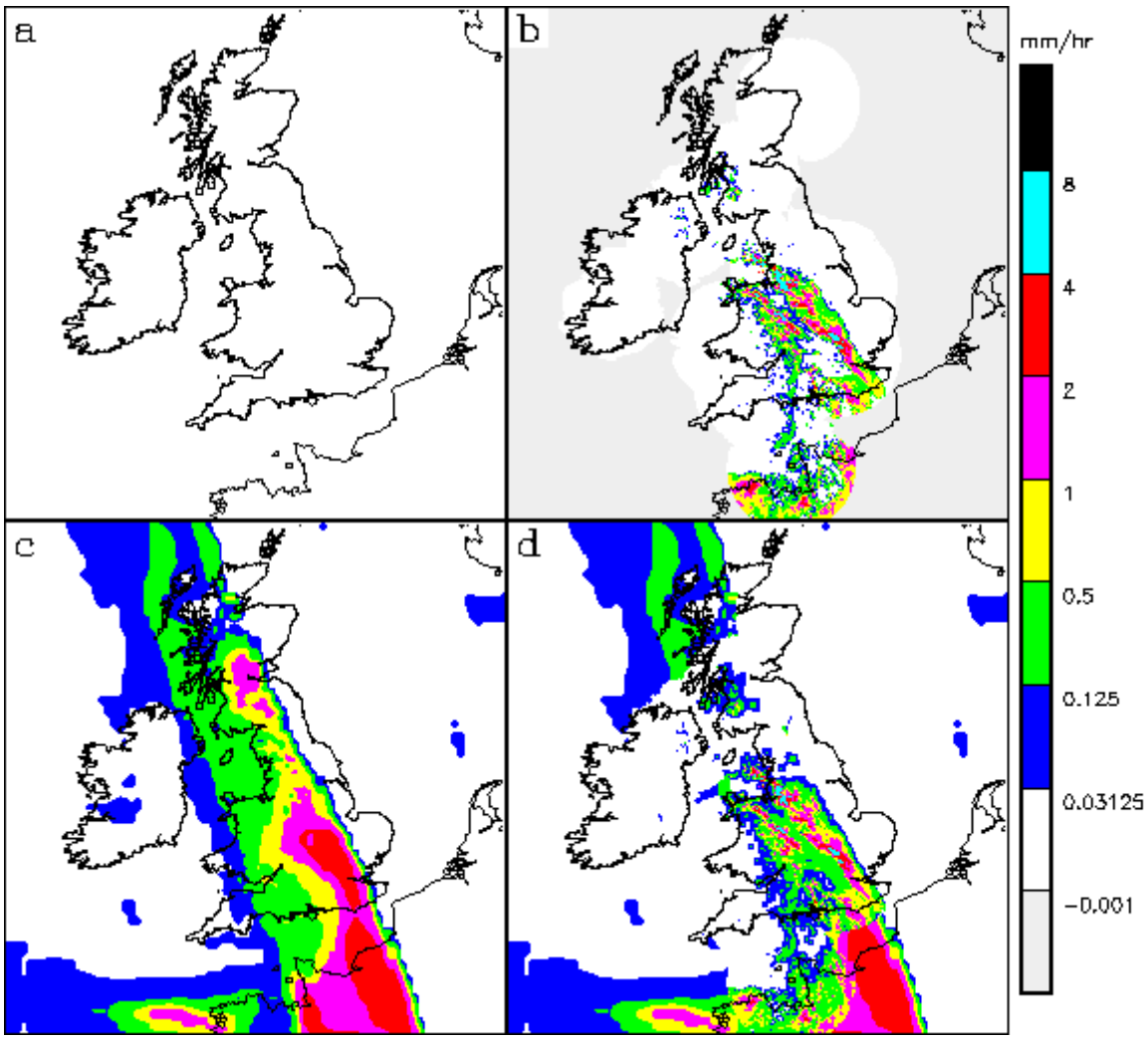

Figure 13: Rainfall Rate ($mm\,hr^{-1}$) for 0700 UTC 11th February 1994: a) Satellite-derived rate, b) Composite Radar image, c) Mesoscale Model forecast, d) Analysis.

2.7 0700 UTC 11th February 1994

A cold front moved in from the west, coming to a halt over the UK, and then sliding southwards, as the precipitation began to die out.

As no satellite data were available for the analysis time, the analysis is purely forecast data outside the radar domain. For this reason, the rain is too heavy and too extensive in the north, and probably a bit too extensive in the south; it may also be too heavy in the south, but there are no observations to confirm this.

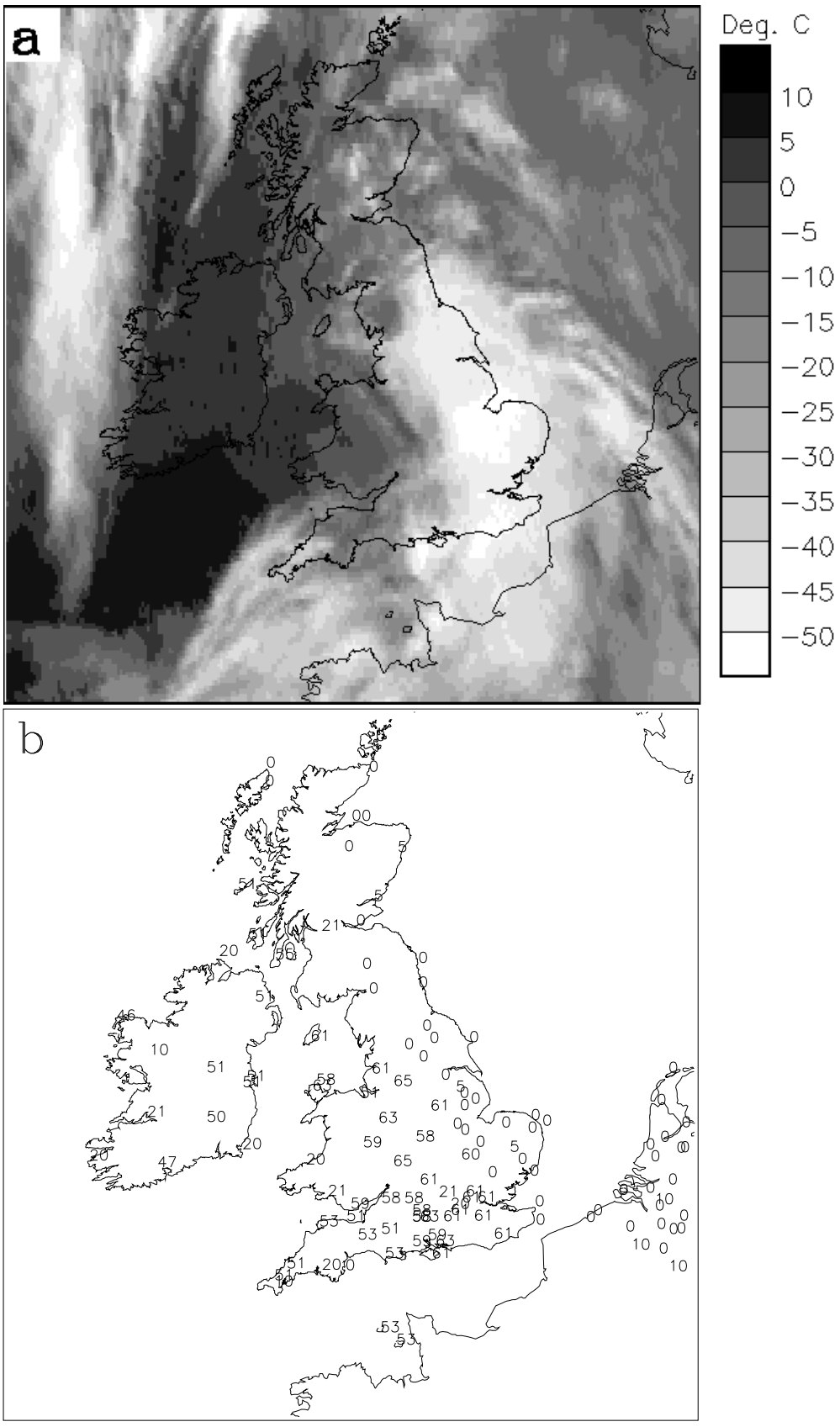

Figure 14: Observations for 0700 UTC 11th February 1994: a) Infrared Meteosat image (0630 UTC), b) Present Weather Code Observations.

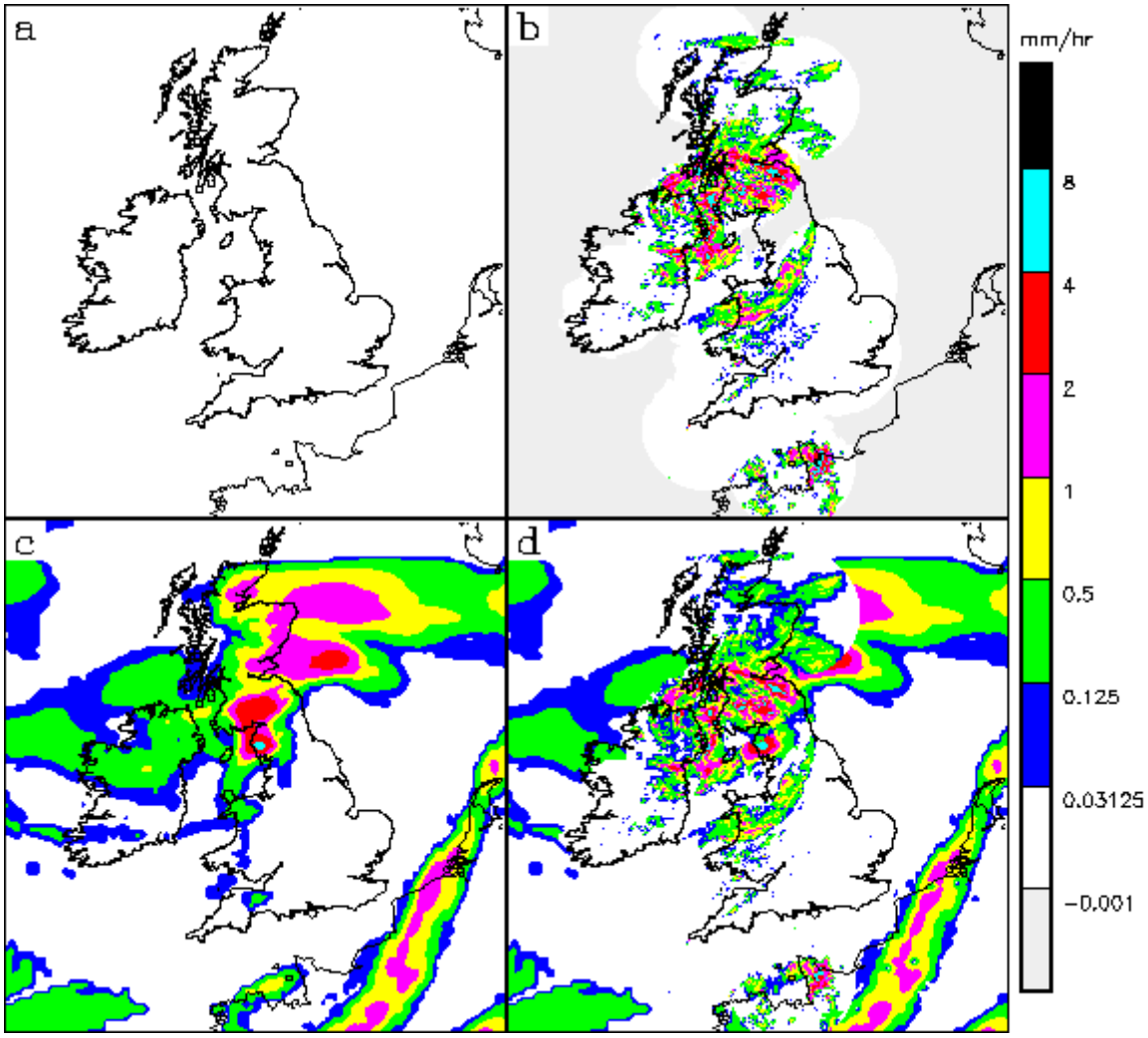

Figure 15: Rainfall Rate ($mm\,hr^{-1}$) for 1500 UTC 27th February 1994: a) Satellite-derived rate, b) Composite Radar image, c) Mesoscale Model forecast, d) Analysis.

2.8 1500 UTC 27th February 1994

A complex frontal system was near-stationary over the UK, with rainbands moving in the circulation.

Once again, no satellite data for the analysis time means that the model forecast is the only source of data outside the radar domain. The T+9 forecast from 0600 UTC does not have a particularly good representation of the complex series of rainbands, so the analysis is not very good outside the radar area. The Present Weather observations suggest that the band of rain over France is not well represented; it can be seen where the surface observations have reduced the rain in the analysis, although their area of influence is quite small.

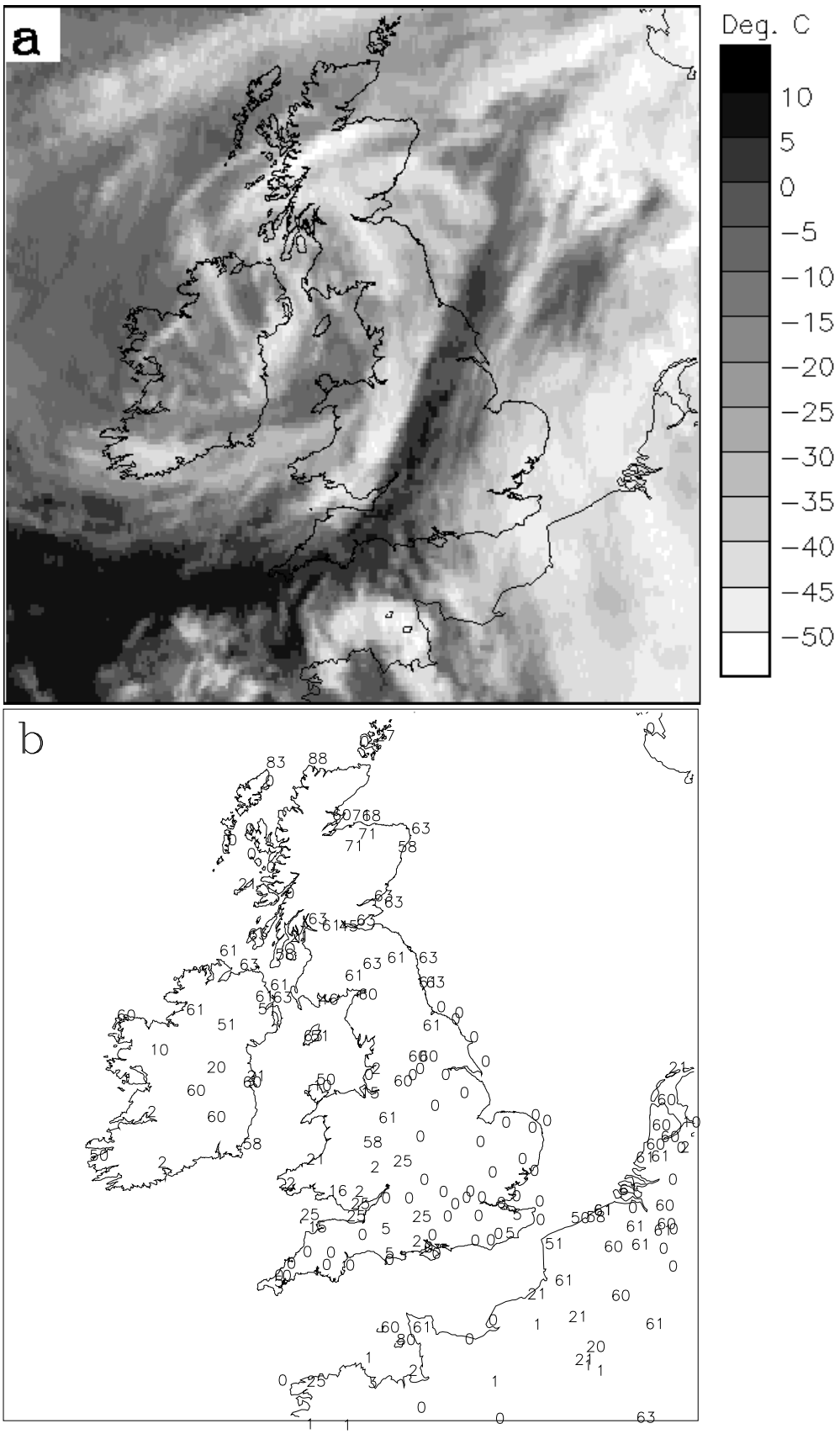

Figure 16: Observations for 1500 UTC 27th February 1994: a) Infrared Meteosat image (1430 UTC), b) Present Weather Code Observations.

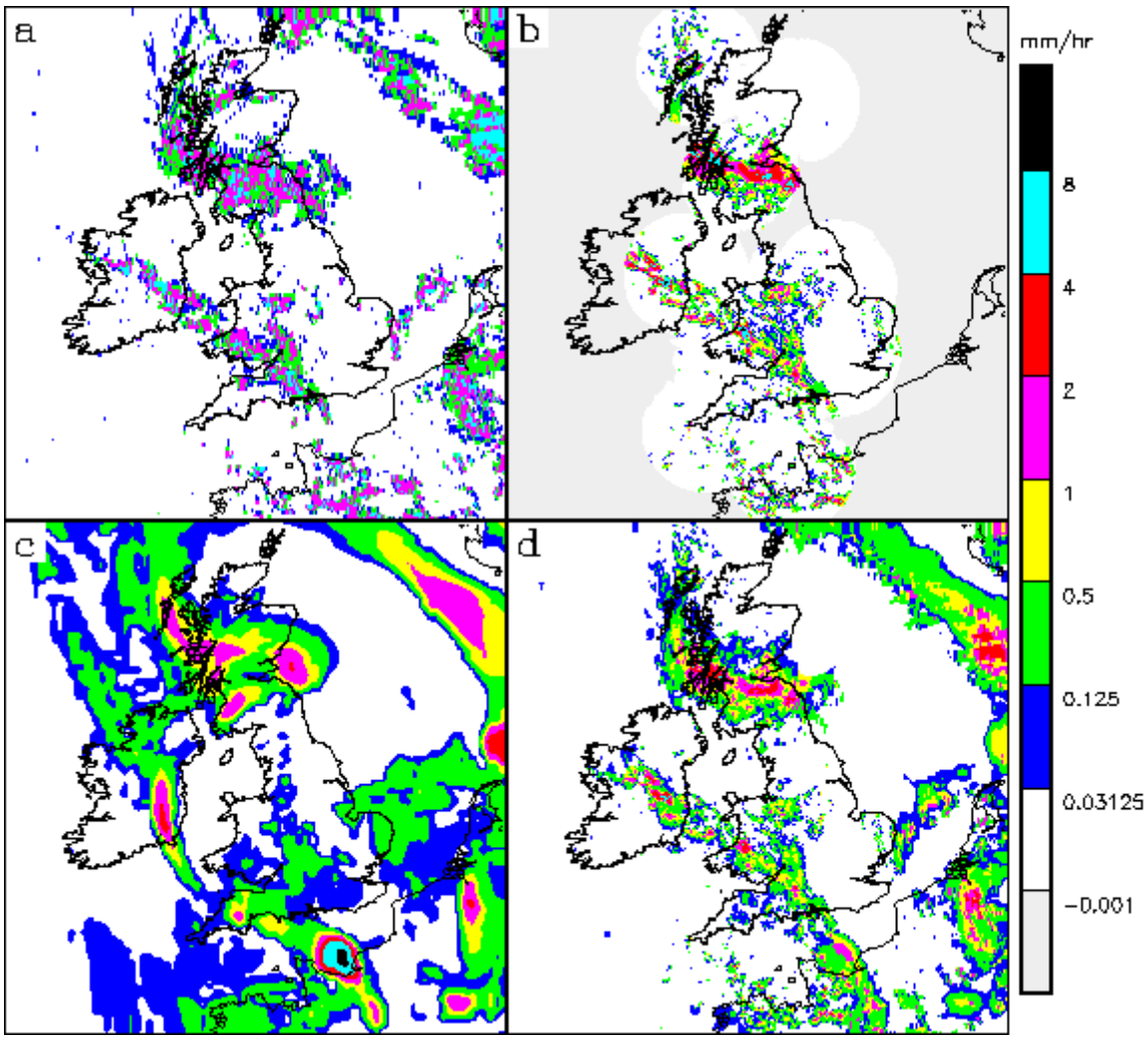

Figure 17: Rainfall Rate ($mm\,hr^{-1}$) for 1200 UTC 9th April 1994: a) Satellite-derived rate, b) Composite Radar image, c) Mesoscale Model forecast, d) Analysis.

2.9 1200 UTC 9th April 1994

The UK and the North Sea were covered by a depression, with a series of rainbands in the circulation.

The analysis is quite good, with the main rainbands being well represented, because the satellite and forecast agree fairly well on their positioning. The erroneous light rain in the forecast in southern England is not present in the analysis. The radar intensities are slightly reduced over Scotland and Wales. The gap in the rainband over the English Channel does not appear in the analysis because the model forecast has a heavy, continuous band.

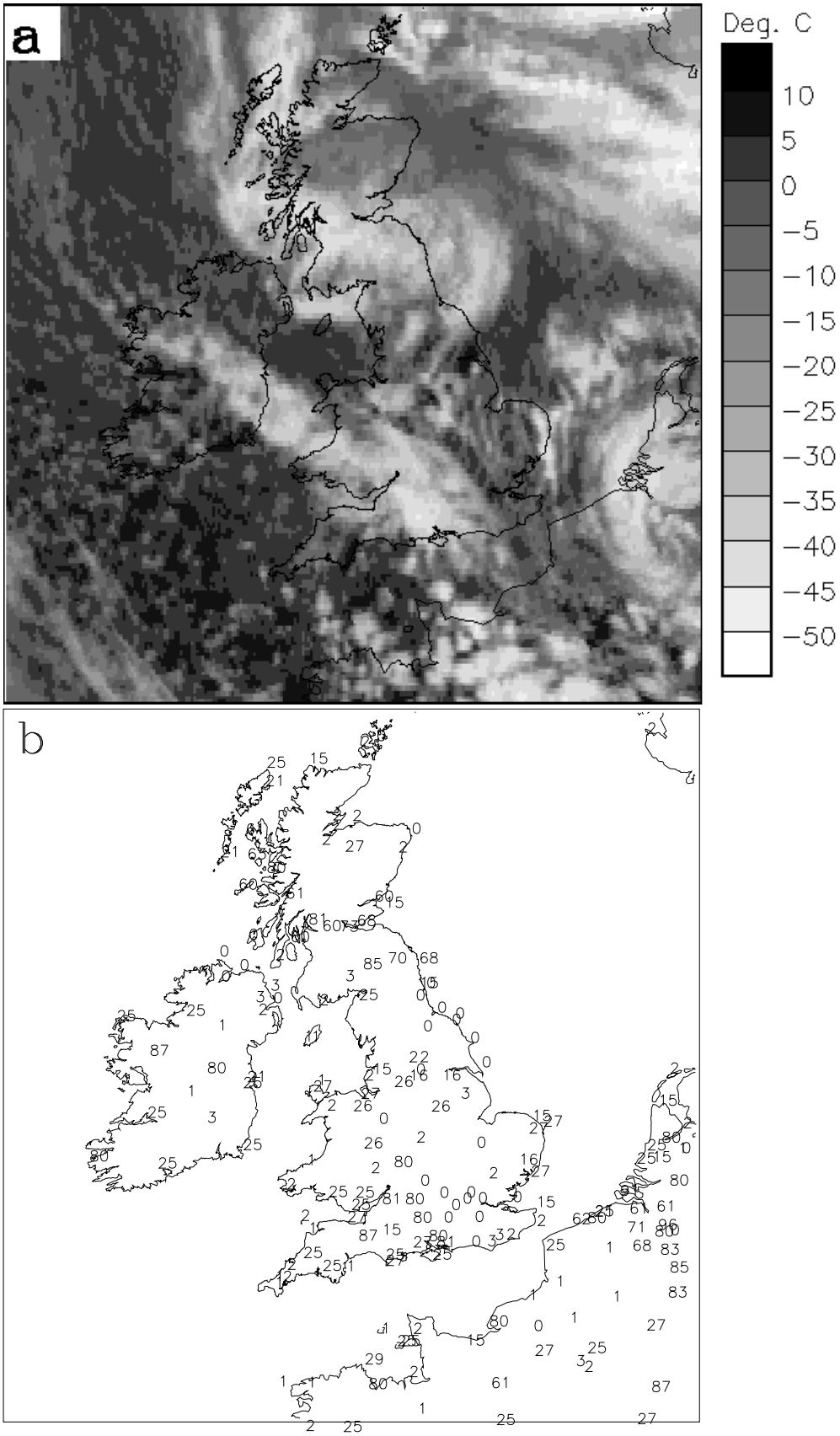

Figure 18: Observations for 1200 UTC 9th April 1994: a) Infrared Meteosat image, b) Present Weather Code Observations.

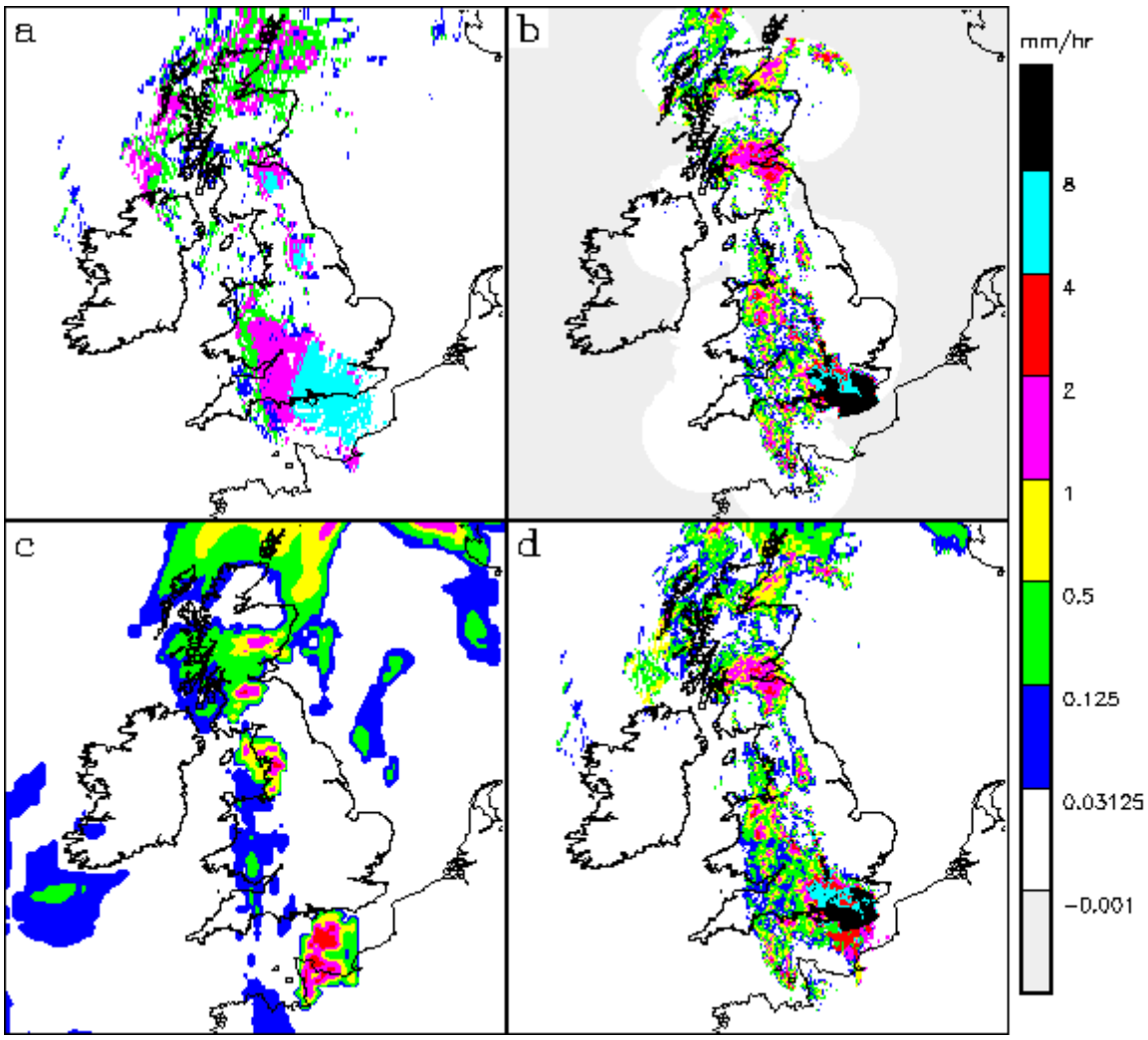

Figure 19: Rainfall Rate ($mm\,hr^{-1}$) for 1900 UTC 24th June 1994: a) Satellite-derived rate, b) Composite Radar image, c) Mesoscale Model forecast, d) Analysis.

2.10 1900 UTC 24th June 1994

As thundery showers moved northwards from France, an intense Mesoscale Convective System (MCS) developed over the English Channel and moved over south-east England.

Virtually all the rain is within the radar domain; the exception, the southern edge of the MCS, appears to be reasonably handled by the combination of satellite and forecast precipitation, although the model forecast (a T+13 from 0600 UTC) does not have the timing of the MCS very well. The radar produces very high rainfall rates (upto 84 $mm\,hr^{-1}$), which are completely wrong (problems with the Chenies radar); these are reduced to 36 $mm\,hr^{-1}$ in the analysis, as a result of the lower rates in the satellite and forecast.

2.11 Summary and Discussion

There are a number of differences between the rainfall rate analysis scheme which would be implemented operationally within Nimrod and that which is used here for testing purposes. These are mainly a result of the data available at the time of testing. The differences, some of which have touched on elsewhere in this report are summarised below:

- The forecast data is taken from a Mesoscale Model forecast (Δr=16.7 km), instead of an advection forecast from the previous analysis (Δr=5 km).

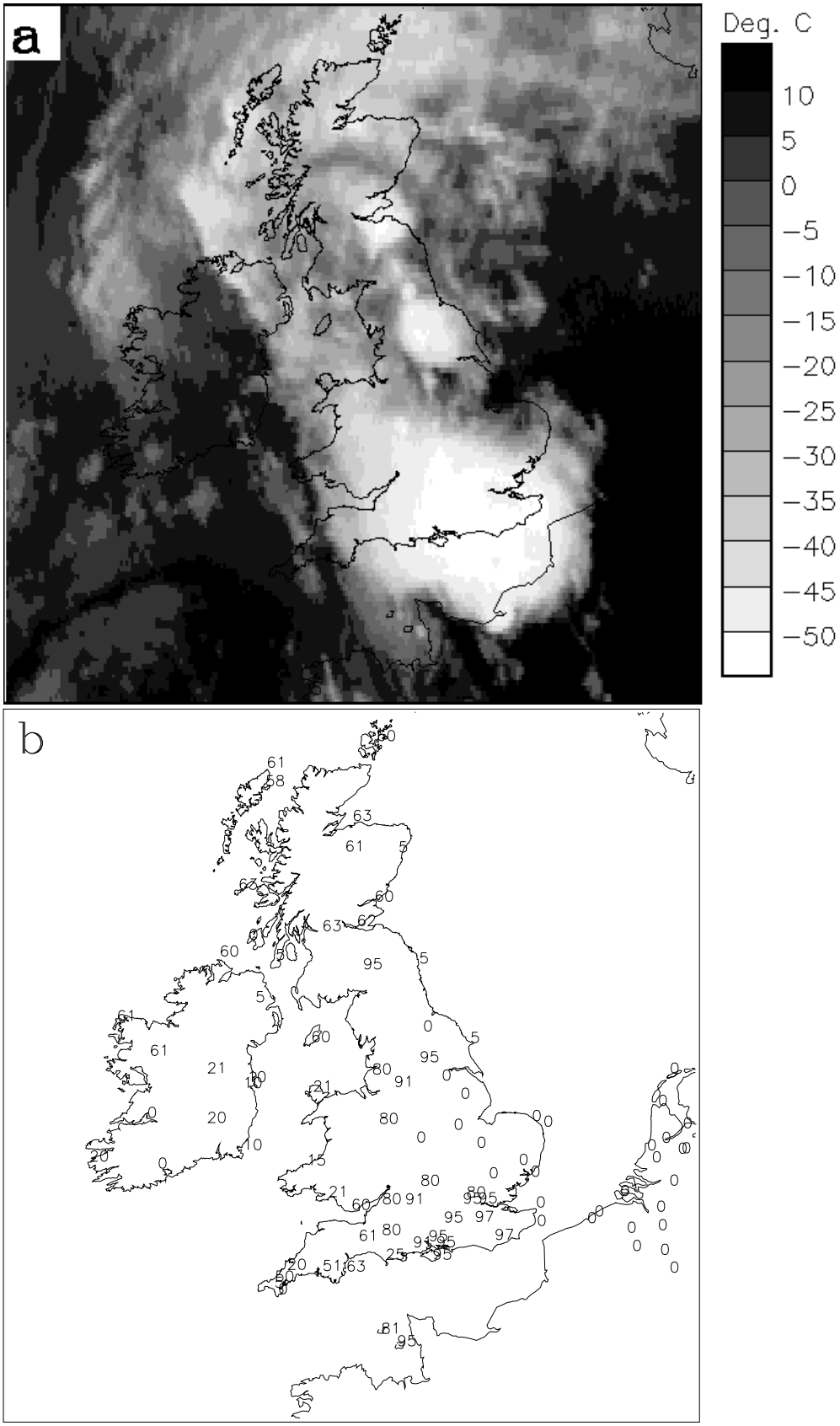

Figure 20: Observations for 1900 UTC 24th June 1994: a) Infrared Meteosat image, b) Present Weather Code Observations.

- No Satellite cloud mask is available to set **w** in dry areas, so it is set in the same way as the forecast and radar (see section 1.2.1).
- The radar data has not had the full set of adjustments (removal of anaprop and correction for 'bright-band', range and gauge measurements) carried out.
- The radar data has a larger Area of Radar Cover (ARC) than it will within Nimrod, where the ARC will be calculated on a case-by-case basis.
- The Test area is smaller than the full Nimrod domain.

The main errors in the analyses shown in the case studies can be divided into five classes:

1. Mis-positioning of rain areas outside the radar domain.
2. Missing rain or incorrect intensities inside the radar domain.
3. Some reduction of radar rainfall rates.
4. Too smooth an analysis, with gaps 'filled in' in showery situations.
5. Not fitting surface observation of light precipitation very well.

Point 1 is primarily due to the use of model forecasts, which, due to the forecast period, can have large timing errors. The use of the Nimrod advection forecast, which is more timely and has used other data sources, should address this. If the infrared and visible satellite data are not well-correlated with the rain areas, then this can also lead to this type of problem. However, in these cases the satellite data should be assigned a higher error variance, because of its correlation with the radar data.

Point 2 is essentially due to errors in the radar data, which are being addressed within Nimrod, by the removal of anaprop and corrections for 'bright-band', range and gauge measurements [5] . Additionally, the valid ranges of the radars (the ARC) will be calculated for each radar image; indeed, it may be possible to use this information to vary the error variances within the radar domain.

Point 3 raises the question of what should be used as the analysis within the radar domain. As long as other data sources are used within the analysis, even with a much higher error variance than the radar data, the analysis will always reflect these data sources.

Point 4 is the result of using a model forecast, which is interpolated from 16.7 km grid. The Nimrod advection forecast, which will be used in its place when the system is implemented will have a higher resolution and should, therefore, have less of a smoothing effect on the analysis. Also, the use of a cloud mask within the satellite rain processing will lead to the cloud-free areas in between showers receiving a 'drier' **w** value, which will tend to suppress rain from other data sources more effectively.

Point 5 is a result of the other data sources overwhelming the surface observations. Many of the Present Weather codes for drizzle and light rain have a lower limit below the lowest radar threshold, which means the analysis may appear dry without such an observation incurring any penalty. It may be appropriate to revise these limits to ensure that an observation of rain does weight the analysis to a 'measurable' rainfall rate.

The acceptance criterion for the rainfall rate analysis presented in the Detailed Plan [4] states:

> ... demonstate that the analysis does not remove any correct rain echoes from the radar composite; that outside the radar coverage, it is, subjectively, at least as good as the sat/rad composite on 95% of occasions, and that, subjectively, it is at least as good as the MOPS 15 km rain analysis on 95% of occasions.

The analysis scheme is strongly weighted towards the radar data, but the forecast, satellite and surface observations will influence it within the radar domain; Although, in general, this is seen as a change in the intensities, it is not impossible for the radar rain to be removed. If it is truly desirable for the analysis to look like the radar within the radar domain, then the radar rainfall rates can be used to overwrite the analysis at the end of the procedure.

The sat/rad composite, consists of the radar data within the radar domain and a single rain threshold ($0.03125\ mm\,hr^{-1}$) taken from satellite data outside. The MOPS rain analysis is produced by replacing the model forecast by the radar rainfall rates within the radar domain, and using this as a background field to analysis the surface observations [13]. This results in a much smoother field than the rainfall

rate analysis demonstrated here, and outside the radar domain, it looks virtually like the original model forecast field. Essentially, outside the radar domain, the sat/rad composite is a single threshold version of the satellite data, and the MOPS analysis is a slightly smoothed version of the model data. Whereas, the Nimrod analysis outside the domain is an unsmoothed combination of the model and four-threshold satellite data. The only instances where either the rad/sat or MOPS data are better than the Nimrod analysis are when either the satellite data is much better than the model data or vice-versa and the 'averaged' field that forms the Nimrod analysis suffers as a result. It is difficult to find a case from the ten discussed here where this has occurred, except for reasons discussed above which will be addressed in the implementation form of the scheme.

3 Conclusions and Further Work

An analysis scheme has been described, which blends radar, satellite and forecast data, surface observations and sferics reports to produce an instantaneous rainfall rate field, using a variational approach.

Ten case studies have been used to assess the performance of the scheme in different synoptic situations. Assessment has been subjective, by necessity. Most of the failing in the case study analyses, are a result of the quality of the data, and are, at least partially, addressed by the planned implementation of the scheme.

The question of quality as compared with the current rad/sat composite and the MOPS rain analysis has been addressed by reasoned argument, rather than direct comparison (which is difficult, without severely limiting the choice of forecasts). These two schemes merge the radar with *either* the model forecast *or* the satellite-derived rainfall rate. The proposed analysis scheme uses the 'best' combination of *both* forecast and satellite.

As tested here, the rainfall rate analysis uses all available data over the full analysis domain. If it is important to preserve the radar rainfall rates, these should be used to overwrite the final analysis within the radar ARC.

The scheme has been developed before most of the Nimrod data sources have become available in their operational form. This has required the use of other, inferior data sources, which have to quite a large extent affected the results, but have allowed the principle of the merging of the data sources to be tested. However, when the scheme is implemented, various parameters, such as the error variance (especially for the forecast), should be re-checked.

The very low rainfall rate thresholds for Present Weather reports of drizzle and light rain, which allow these observations to be 'fitted' whilst producing a 'dry' analysis, should be revised upwards.

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